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WIND-TUNNEL INVESTIGATION OF CONTROL-SURFACE CHARACTERISTICS

XIV - NACA 0009 AIRFOIL WITH A 20-PERCENT-CHORD

DOUBLE PLAIN FLAP

By Richard I. Sears and Paul E. Purser

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NATIONAL ADVISORY COMMITTEE FOR AERONAUTICS

ADVANCE RESTRICTED REPORT

WIND-TUNNEL INVESTIGATION OF CONTROL-SURFACE CHARACTERISTICS

XIV - NACA 0009 AIRFOIL WITH A 20-PERCENT-CHORD

DOUBLE PLAIN FLAP

By Richard I. Sears and Paul E. Purser

SUMMARY

Force-test measurements in two-dimensional flow have been made in the NACA 4- by 6-foot vertical tunnel to determine the aerodynamic characteristics of an NACA 0009 airfoil equipped with a double plain flap that consisted of a plain forward flap having a chord 20 percent of the airfoil chord (0.20c) and a plain rearward flap having a chord 15 percent of the airfoil chord,

The results of the present tests and a brief analysis of previously obtained data indicated that, for positive flap deflections at zero and positive angles of attack, a sealed 0.20c double plain flap would produce more lift and less hinge moment than a 0.50c single plain flap. The small double flap was not so effective as the large plain flap in producing positive lift at large negative angles of attack. With controls free, the slope of the lift curve of a surface having a 0.20c single or a 0.20c double plain flap is more than twice that of a surface having a 0.50c plain flap. Although the stick hinge moments of a small-chord double plain flap are much less than those of a larger-chord single plain flap, they are still too great for use on large high-speed airplanes. In order to function efficiently both gaps of double plain flaps should be sealed.

INTRODUCTION

The conventional control surfaces used on most airplanes consist of single flaps that generally have some type of aerodynamic balance and small tabs for trim or balance. The maximum deflections of these surfaces have been fairly well standardized at about 15° or 20° for

1-2-30

ailerons and at about 25° or 30° for elevators and rudders. These deflections in turn define the mechanical advantage of the control surfaces over the control stick or pedals. The ratio of control area to airfoil area therefore must be sufficiently large that, with these maximum deflections, the control surfaces are capable of producing the lifts necessary for proper control at critical operating conditions.

An analysis of data in references 1 to 3 indicates that, if a small-chord control surface is allowed to deflect considerably more than 30° or if two flaps are allowed to deflect simultaneously in the same direction, greater lifts and smaller stick forces can be obtained with small-chord flaps than can be obtained with conventional control surfaces deflected the conventional amounts already stated.

The purpose of this paper is to show the extent to which improved control characteristics can be obtained by departing from the customary control-surface sizes and the customary ranges of control-surface deflection. Throughout the paper, the conventional control surfaces already mentioned are used as a basis for comparison with proposed arrangements.

APPARATUS AND MODEL

The tests were made in the NACA 4- by 6-foot vertical tunnel (reference 4). The test section of this tunnel has been converted from the original open, circular, 5-foot-diameter jet to a closed, rectangular, 4- by 6-foot throat for force tests of models in two-dimensional flow. A three-component balance system has been installed in the tunnel in order that force-test measurements of lift, drag, and pitching moment may be made. The hinge moments of both flaps were measured with electrically indicating, cantilever-beam, wire strain gages.

The 2-foot-chord by 4-foot-span model (fig. 1) was made of laminated mahogany to the NACA 0009 airfoil contour. The forward and rearward flaps were also built of mahogany and their respective chords were 20 percent of the airfoil chord (0.20c) and 15 percent of the airfoil chord (0.15c). The 0.005c gaps between the airfoil and the forward flap and between the forward and the rearward

flaps were sealed with grease for some tests and were left open for others.

TESTS

The NACA 0009 airfoil with the 0.20c forward flap and the 0.15c rearward flap, when mounted in the tunnel, completely spanned the test section. With this type of test installation, two-dimensional flow is approximated and the section characteristics of the model may be determined. The model was attached to the balance frame by torque tubes that extended through the sides of the tunnel. The angle of attack was set from outside the tunnel by rotating the torque tubes with an electric drive. Deflections of each flap were set inside the tunnel by templates and were held by friction clamps.

The tests were made at a dynamic pressure of 15 pounds per square foot, which corresponds to a velocity of about 76 miles per hour. The effective Reynolds number of the tests was approximately 2,780,000. (Effective Reynolds number = test Reynolds number \times turbulence factor. The turbulence factor for the NACA 4- by 6-foot vertical tunnel is 1.93.)

The tests were made at the flap deflections indicated in figure 2. The values of lift, drag, pitching moment, and both flap hinge moments were read for all tests throughout the angle-of-attack range from negative stall to positive stall. All readings were taken at 2° increments of angle of attack except near the stall, where the increment was reduced to 1° .

RESULTS

Symbols

The coefficients and the symbols used in this paper are defined as follows:

c_l airfoil section lift coefficient (l/qc)

c_{d_0} airfoil section profile-drag coefficient (d_0/qc)

c_m airfoil section pitching-moment coefficient (m/qc^2)

- c_{h_1} forward-flap section hinge-moment coefficient (h_1/qc_1^2)
 c_{H_1} forward-flap section hinge-moment coefficient (h_1/qc^2)
 c_{h_2} rearward-flap section hinge-moment coefficient (h_2/qc_2^2)
 c_{H_2} rearward-flap section hinge-moment coefficient (h_2/qc^2)
 c_{H_s} control-stick (or pedal) hinge-moment coefficient
 (H_s/qc^2) (See equation (2).)

where

- l airfoil section ~~length~~
 d_0 airfoil section profile drag
 m airfoil section pitching moment about quarter-chord point of airfoil
 h_1 forward-flap section hinge moment
 h_2 rearward-flap section hinge moment
 H_s control-stick (or pedal) hinge moment
 c chord of basic airfoil with both flaps neutral
 c_1 chord of forward flap with rearward flap neutral
 c_2 chord of rearward flap
 q dynamic pressure

and

- α_0 angle of attack for airfoil of infinite aspect ratio
 δ flap deflection with respect to surface ahead
 δ_1 deflection of forward flap with respect to airfoil
 δ_2 deflection of rearward flap with respect to forward flap

δ_s deflection of an aerodynamically equivalent single-flap control surface having a deflection equal to that of the control stick

also

$$c_{l\alpha} = \left(\frac{\partial c_l}{\partial \alpha_0} \right)_{\delta_1, \delta_2}$$

$$\alpha_{\delta_1} = \left(\frac{\partial \alpha_0}{\partial \delta_1} \right)_{c_l, \delta_2}$$

$$\alpha_{\delta_2} = \left(\frac{\partial \alpha_0}{\partial \delta_2} \right)_{c_l, \delta_1}$$

$$\alpha_{\delta_s} = \left(\frac{\partial \alpha_0}{\partial \delta_s} \right)_{c_l}$$

$$c_{h_1\alpha} = \left(\frac{\partial c_{h_1}}{\partial \alpha_0} \right)_{\delta_1, \delta_2}$$

$$c_{h_2\alpha} = \left(\frac{\partial c_{h_2}}{\partial \alpha_0} \right)_{\delta_1, \delta_2}$$

$$c_{h_1\delta_1} = \left(\frac{\partial c_{h_1}}{\partial \delta_1} \right)_{\alpha_0, \delta_2}$$

$$c_{h_1\delta_2} = \left(\frac{\partial c_{h_1}}{\partial \delta_2} \right)_{\alpha_0, \delta_1}$$

$$c_{h_2\delta_2} = \left(\frac{\partial c_{h_2}}{\partial \delta_2} \right)_{\alpha_0, \delta_1}$$

$$c_{h_2\delta_1} = \left(\frac{\partial c_{h_2}}{\partial \delta_1} \right)_{\alpha_0, \delta_2}$$

$$c_{H_s\alpha} = \left(\frac{\partial c_{H_s}}{\partial \alpha_0} \right)_{\delta_s}$$

$$c_{H_s\delta_s} = \left(\frac{\partial c_{H_s}}{\partial \delta_s} \right)$$

The subscripts outside the parentheses around the parameters indicate the factors held constant during the measurement of the parameters. Throughout this paper, "control stick" is used as a general term for the control-surface actuating device, whether it be a stick, a wheel, or pedals.

Precision

The accuracy of the data is indicated by the deviation from zero of the lift and moment coefficients at an angle of attack of 0° with both flaps neutral. The maximum error in effective angle of attack at zero lift appears to be about $\pm 0.3^\circ$. Deflections of the flaps were set to an accuracy of $\pm 0.2^\circ$. Tunnel corrections, experimentally determined in the NACA 4- by 6-foot vertical tunnel, were applied only to the lift. The hinge moments are probably slightly higher than would be obtained in free air and the values presented are consequently considered conservative. The drag values are subject to unknown tunnel and turbulence corrections.

Presentation of Data

The aerodynamic section characteristics of the NACA 0009 airfoil with the 0.20c plain forward flap and the 0.15c plain rearward flap, both having unsealed gaps, are presented in figure 3. The characteristics of the airfoil with both flaps sealed and deflecting together are given in figure 4(a) for $d\delta_2/d\delta_1 = 1$ and in figure 4(b) for $d\delta_2/d\delta_1 = 2$. The characteristics of the airfoil with the forward flap sealed and locked neutral for various deflections of the unsealed and sealed rearward flap are presented in figure 5; similar characteristics of the airfoil with the rearward flap sealed and neutral for various deflections of the unsealed and sealed forward flap are presented in figure 6. Figures 7 and 8 show comparison curves of the lift available from given flap deflections and of the stick hinge moment required to produce given lift increments for 0.50c, 0.30c, 0.20c, and 0.15c plain flaps and for several arrangements of double plain flaps. Comparisons similar to those of figures 7 and 8 are given in tables I and II in the form of the various lift and hinge-moment parameters, which are applicable over only a small range of α and δ . A comparison of the drag characteristics of the various single and double flaps at an angle of attack of 0° is presented in figure 9.

DISCUSSION

Lift

The aerodynamic characteristics of various double-flap control systems that consist of a 0.20c plain forward flap and a 0.15c plain rearward flap deflecting at various rates with respect to the control stick can be estimated from the test data presented in figures 3 and 4. These data indicate that the slope of the lift curve $c_l \alpha$ (table I) is in agreement with that measured from previous tests (reference 5) when both gaps are sealed or when one gap is open. When both gaps are open, however, a lower slope is obtained than for the other gap conditions mentioned. At large positive flap deflections for large negative angles of attack, the slope $c_l \alpha$ becomes very great regardless of gap condition. This effect is characteristic of small-chord flaps (reference 6).

Throughout the angle-of-attack range, an increase in the deflection of either flap caused an increase in airfoil-section lift until the sum of the deflections of both flaps reached about 70° . As usual, the increments of lift per unit flap deflection became smaller as the flap deflection became larger. A summary of lift-effectiveness parameters $(\alpha_\delta)_{c_l}$ for each flap deflected alone with the various gap conditions tested is included in table I. The values for each flap with sealed gap check well with those predicted from the data presented in reference 7. The lift effectiveness of both flaps decreased when the gap at the nose was unsealed. The forward flap showed a still further decrease in lift effectiveness but the rearward flap did not when both gaps were open. The effectiveness of a double-flap combination may be expressed in terms of the effectiveness of each flap and the relative rates of deflection. Thus

$$\begin{aligned} \alpha_{\delta_s} &= \alpha_{\delta_1} \frac{d\delta_1}{d\delta_s} + \alpha_{\delta_2} \frac{d\delta_2}{d\delta_s} \\ &= \left(\alpha_{\delta_1} + \alpha_{\delta_2} \frac{d\delta_2}{d\delta_1} \right) \frac{d\delta_1}{d\delta_s} \end{aligned} \quad (1)$$

An inspection of figure 7 indicates that either the 0.20c single-flap or the 0.20c double-flap arrangement is capable of producing lift as great or greater than a 0.50c plain flap deflected 30° at zero or positive angles of attack. At a large negative angle of attack with positive flap deflections - the attitude of an elevator for landing - the 0.20c single or the 0.20c double flap produces as much positive lift as the 0.50c plain flap deflected 17°. It should be pointed out that increments of lift as large as those obtained with a 0.50c plain flap cannot be obtained with any known type of aerodynamic balance on a 0.50c flap. Because of unporting difficulties and separation phenomena, the maximum usable deflection of a balanced 0.50c flap is about 15°. With the horn type of aerodynamic balance, however, a 0.50c flap is effective in producing increments of lift to a positive deflection of 30° at negative angles of attack and to a positive deflection of 20° at zero and positive angles of attack. The lift obtainable with a 0.20c single or a 0.20c double flap therefore is believed equal to or greater than that with a balanced 0.50c flap except when the 0.50c flap has a horn balance. The 0.20c single or the 0.20c double flap is capable of producing much greater positive lift than a 0.30c plain flap deflected 30° at zero and positive angles of attack but, as a large negative

For a given lift effectiveness per unit stick deflection are indicative of the deflection rates $\delta\ell/\delta\theta$ required items of particular interest. The slopes of the lift curves degrees to which each lift curve departs from linearity are unsealed gap. The maximum lift for each flap and the surfaces. No data were available for a 0.50c flap with lifts that are currently obtained from conventional tail been included because they are considered typical of the 0.30c and a 0.50c flap deflected to a maximum of 30° have references 1, 2, and 5. The lift characteristics of a the present test results and from results presented in The lift comparison given in figure 7 was taken from

The data indicate that equation (1) gives good agreement with test results when both gaps are open but tends to underestimate the resultant effectiveness when both gaps are sealed. It is obvious from equation (1) that, by varying the rate of deflection $\delta\ell/\delta\theta$, either a single or a double flap can be made to give any desired resultant lift effectiveness per unit stick deflection $\alpha\delta\theta$.

angle of attack, all flaps of this group produce about the same positive lift. A 0.15c single flap produces considerably more lift when deflected positively 60° at zero and positive angles of attack than does a 0.30c flap deflected 30° . At a large negative angle of attack, the 0.30c flap produces greater lift.

Hinge Moments

The test points for the flap hinge-moment coefficients plotted in figures 3 to 6 are in some cases somewhat erratically dispersed about the faired curves. A large part of this dispersion was caused by continued improper functioning of the electrical strain-gage units that were used in measuring the hinge moments. In fairing the curves some of the test points believed to be in error have been disregarded. It was not considered worth the time and the effort required to check each doubtful hinge-moment test point because, for this investigation, lift rather than hinge-moment characteristics were of primary importance. The hinge-moment curves of figure 3(e) for $\delta_a = 20^\circ$ and of figure 3(f) for $\delta_a = 25^\circ$ appear to be in error, although the tests were repeated throughout the angle-of-attack range. It is believed that the data presented adequately define the hinge-moment characteristics of the unbalanced flaps tested.

The hinge moments of the 0.20c and the 0.15c flaps change very little with angle of attack for low flap deflections; hence, these small-chord flaps have very little floating tendency. At large positive deflections, the hinge moments change rapidly from a large negative value at zero and positive lifts to almost zero at large negative lifts. This rapid change of hinge-moment coefficient occurs in the same lift range and at the same large flap deflections for which the slope of the lift curve cl_α becomes excessively steep. Whether the hinge-moment coefficient will reach a sufficiently large positive value at large, stalled, negative angles of attack to give rudder lock remains a subject for further investigation. These data indicate that, at the negative stall, the hinge-moment coefficient for all positive deflections is nearly zero. Even if the control surface should blow over at the stall, therefore, little force would be required to bring the control back to zero deflection.

The hinge-moment slopes measured at small angles of attack and at small deflections are presented in table I for various gap conditions. The slopes $c_{h\alpha}$ and $c_{h\delta}$ for the flaps with sealed gaps are in close agreement with those predicted from the parameters presented in reference 7. The slopes given in table I can be used to estimate relative characteristics of double-flap control systems of the type considered. In dealing with the hinge moments of double-flap systems, it is convenient to compute the stick hinge moment, which in effect is the hinge moment of an aerodynamically equivalent single-flap control surface having a deflection equal to the deflection of the control stick. The stick hinge-moment coefficient based on airfoil chord is then

$$\begin{aligned} c_{H_s} &= c_{h_1} \left(\frac{c_1}{c} \right)^2 \frac{d\delta_1}{d\delta_s} + c_{h_2} \left(\frac{c_2}{c} \right)^2 \frac{d\delta_2}{d\delta_s} \\ &= c_{H_1} \frac{d\delta_1}{d\delta_s} + c_{H_2} \frac{d\delta_2}{d\delta_s} \\ &= \left(c_{H_1} + c_{H_2} \frac{d\delta_2}{d\delta_1} \right) \frac{d\delta_1}{d\delta_s} \end{aligned} \quad (2)$$

It can be shown that the rate of change of stick hinge-moment coefficient with stick deflection is

$$\begin{aligned} c_{H_s \delta_s} &= c_{H_1 \delta_1} \left(\frac{d\delta_1}{d\delta_s} \right)^2 + \left(c_{H_1 \delta_2} + c_{H_2 \delta_1} \right) \frac{d\delta_1}{d\delta_s} \frac{d\delta_2}{d\delta_s} + c_{H_2 \delta_2} \left(\frac{d\delta_2}{d\delta_s} \right)^2 \\ &= \left(\frac{d\delta_1}{d\delta_s} \right)^2 \left[\left(\frac{c_1}{c} \right)^2 \left(c_{h_1 \delta_1} + c_{h_1 \delta_2} \frac{d\delta_2}{d\delta_1} \right) + \left(\frac{c_2}{c} \right)^2 \left(c_{h_2 \delta_1} + c_{h_2 \delta_2} \frac{d\delta_2}{d\delta_1} \right) \frac{d\delta_2}{d\delta_1} \right] \end{aligned} \quad (3)$$

The values of the hinge-moment terms $c_{h_1 \delta_1} + c_{h_1 \delta_2} \frac{d\delta_2}{d\delta_1}$ and $c_{h_2 \delta_1} + c_{h_2 \delta_2} \frac{d\delta_2}{d\delta_1}$ of equation (3) can be read directly

from the curves presented in figures 3 to 6. The rate of change of stick-hinge-moment coefficient with angle of attack may be expressed as

$$c_{H_{s\alpha}} = c_{H_1\alpha} \frac{d\delta_1}{d\delta_s} + c_{H_2\alpha} \frac{d\delta_2}{d\delta_1}$$

$$= \frac{d\delta_1}{d\delta_s} \left[\left(\frac{c_1}{c} \right)^2 c_{h_1\alpha} + \left(\frac{c_2}{c} \right)^2 c_{h_2\alpha} \frac{d\delta_2}{d\delta_1} \right] \quad (4)$$

The parameters $c_{h_1\alpha}$ and $c_{h_2\alpha}$ measured from the data presented in figures 3 to 6 are given in table I.

Table II has been computed from the data of the present report and of references 1, 2, and 5 by means of equations (1) to (4) and the following relationships:

$$\left(c_{H_{scl}} \right)_{\delta_s} = \frac{\left(c_{H_{s\alpha}} \right)_{\delta_s}}{\left(c_{l\alpha} \right)_{\delta_s}} \quad (5)$$

$$\left(c_{H_{s\delta_s}} \right)_{cl} = \left(c_{H_{s\delta_s}} \right)_{\alpha} + \left(c_{H_{s\alpha}} \right)_{\delta_s} \left(\alpha_{\delta_s} \right)_{cl} \quad (6)$$

$$\left(c_{l\alpha} \right)_{free} = \left(c_{l\alpha} \right)_{\delta_s} \left[1 + \left(\alpha_{\delta_s} \right)_{cl} \frac{\left(c_{H_{s\alpha}} \right)_{\delta_s}}{\left(c_{H_{s\delta_s}} \right)_{\alpha}} \right] \quad (7)$$

The rate of deflection $d\delta_1/d\delta_s$ for each of the control surfaces given in table II has been adjusted in accordance with equation (1) in order that each surface gives $\alpha_{\delta_s} = -0.77$, which is the lift effectiveness of a sealed 0.50c plain flap.

The parameters in table II are a direct measure of the relative stick forces of the various control-surface arrangements having the same lift effectiveness; the effects of control chord and mechanical advantage have been taken into account by equations (1) and (2). Table II indicates that, although the value of $c_{H_s\alpha}$ for a

0.50c plain flap can be reduced by using a 0.50c double flap, the rearward flap of the combination was too small to give an appreciable reduction in $c_{H_s\delta_s}$. Because

$(c_{H_s\alpha})_{\delta_s}$ has been reduced without a comparable reduction in $(c_{H_s\delta_s})_{\alpha}$, the value of $(c_{H_s\delta_s})_{c_l}$, which is a meas-

ure of aileron stick forces in rolling, has actually been increased over that of the plain flap. The 0.30c single and the 0.30c double flaps show appreciable reduction in hinge-moment parameters over those for the 0.50c plain flap. Here again the rearward flap of the combination was too small to give an appreciable reduction in $(c_{H_s\delta_s})_{\alpha}$

over that of the single flap. The 0.20c double flap tested was designed to have a rearward flap sufficiently large that reduction in $(c_{H_s\delta_s})_{\alpha}$ over that of a 0.20c single

flap could be realized. The results indicate that such reductions occurred when the gaps were sealed. Introducing a second gap to make a double flap from a single unsealed flap had decidedly adverse effects both on lift and on hinge moment. In order to work effectively, double plain flaps must be sealed. The sealed 0.20c double flap gave less than one-fourth the value of $(c_{H_s\delta_s})_{\alpha}$, about one-sixteenth the value of $(c_{H_s\alpha})_{\delta_s}$, and about one-half the value of $(c_{H_s\delta_s})_{c_l}$ that the 0.50c plain flap gave.

The lift effectiveness $\alpha\delta_s$ of the sealed 0.20c double and the 0.50c plain flaps is the same and the maximum lift characteristics at various angles of attack have already been discussed. The value of $(c_{l\alpha})_{\text{free}}$, which is proportional to the control-free stability of the airplane, has been increased from 0.038 for the 0.50c plain flap to 0.082 for the 0.20c double flap. Because of a great reduction in floating tendency, the airplane control-free stability can be more than doubled by using a small-chord single- or double-flap control surface rather than a large-chord single-flap surface.

The lift-producing characteristics of small-chord single and double flaps have been compared with those of typical conventional control surfaces in figure 7. The stick hinge-moment curves of these same flaps are compared in figure 8 at three angles of attack when the rate of deflection $d\delta_1/d\delta_2$ of each has been adjusted to give nearly the maximum available lift to each arrangement for the critical operating conditions. These maximum-lift characteristics, which are nearly the same for all arrangements, have already been discussed. In interpreting these curves, it should be remembered that the control stick is assumed to be limited to a maximum deflection of 30° and that the stick hinge moment takes account of the mechanical advantage; therefore, no extrapolation of the curves to higher lift is justified without increasing the slope of the whole curve in accordance with the consequent increased mechanical advantage of the control surface over the control stick. Conversely, if these curves are shortened by decreasing $\delta_{1\max}$, and hence $c_{l\max}$, a corresponding decrease in the slope of each curve can be realized.

The data shown in figure 8 indicate that, for positive deflections at attitudes which are critical for rudder ($\alpha_0 = 0^\circ$ and 8°), the stick hinge moment of a 0.50c flap is many times as great as that of a 0.20c double flap. At attitudes that are critical for elevator ($\alpha_0 = -12^\circ$), however, the stick hinge moments of the double-flap arrangements lie between those of the 0.50c and the 0.30c plain flaps. It should be noted that small hinge moments are obtained from the 0.30c and the 0.50c flaps at $\alpha_0 = -12^\circ$ only because of the large floating tendencies of these flaps; whereas the 0.20c double flaps do not float appreciably. At $\alpha_0 = 8^\circ$, the floating tendency of the large-chord single flap acts to increase the stick hinge moment. The stick hinge moments of the 0.50c, the 0.30c, and the 0.20c single flaps increase suddenly when a preliminary air-flow separation apparently occurs at about the middle of the deflection range; whereas the c_{H_δ} -curve for the double flap is nearly linear. At small deflections, the 0.20c double flap has about the same stick hinge moment as the 0.20c single flap but, at large deflections, the stick hinge moment of the double flap is decidedly less. This fact is true with either sealed or open gaps. With open gaps, the hinge-moment curves for the double flap are nearly coincident regardless of the relative rate of deflection of the two flaps $d\delta_2/d\delta_1$. With sealed gaps, the double flap

tended to give less stick hinge moment when the rearward flap moved faster than the forward one. Table II indicates that, when $d\delta_1/d\delta_2$ was adjusted to give the same $\alpha\delta_2$ for each arrangement, however, the stick-moment parameters were about the same.

Although the stick hinge moments of the 0.20c double plain flap are much smaller than those of the 0.50c and 0.30c plain flaps, they are not small enough for use as rudders or elevators on large high-speed airplanes. The double flap is, however, well adapted for use with the overhang (inset hinge) or the internal type of aerodynamic balance. It is believed that tests of such arrangements are warranted on the basis of the promising results obtained from the present investigation. A small-chord balanced double flap of large lift effectiveness should make a desirable aileron because the aileron span may be decreased in proportion to the increased lift effectiveness and thereby may permit the use of large-span high-lift devices on the wing.

Drag

The drag of each single- and double-flap arrangement tested has been plotted for unstalled angles of attack in figures 3 to 6. A cross plot of drag data at an angle of attack of 0° is presented in figure 9 for various single- and double-flap arrangements. Unfortunately, no profile-drag data for a 0.50c flap were available for comparison. Figure 9 shows that, with sealed gap and at small lift coefficients ($c_l < 0.4$), the drag of all arrangements was nearly the same. At large lift coefficients, the double-flap arrangement with the rearward flap deflected twice as far as the forward flap gave the least drag. The favorable pressure gradient ahead of the hinge of the rearward flap therefore apparently delays separation of air flow because, at a given large c_l , the 0.20c double flap with $d\delta_2/d\delta_1 = 1$ gave less drag than the 0.20c single flap, and the double flap with $d\delta_2/d\delta_1 = 2$ in turn gave less drag than that with $d\delta_2/d\delta_1 = 1$. The drag characteristics at other angles of attack were similar to those shown in figure 9 for an angle of attack of 0° .

With open gap, however, the double flap still gave less drag at large lifts than the single flaps, although increasing the rate of deflection of the rearward flap

increased the drag. It should be remembered that, in the open-gap condition, the double flap had two gaps open; whereas the single flap had only one gap open.

Pitching Moments

The pitching-moment curves (figs. 3 to 6) are somewhat similar to the hinge-moment curves in that they are linear for low flap deflections and change rapidly with lift coefficient at large flap deflections in the range in which $c_{l\alpha}$ becomes very steep. The curves are characteristic of small-chord flaps (reference 6). Pitching-moment parameters measured from the data of figures 3 to 6 are given in table I. For small flap deflections, the aerodynamic center of the lift caused by change in angle of attack was located between the 0.23c and the 0.24c stations regardless of gap condition. This aerodynamic center shifts rearward at large flap deflections when $c_{l\alpha}$ becomes very steep. When trimmed in the landing attitude, an airplane with a small-chord elevator should therefore experience increased stability for two reasons: first and most important, the slope of the lift curve of the tail increases markedly and, secondly, the aerodynamic center of the tail moves rearward. The aerodynamic center of the lift caused by change in flap deflection with sealed gaps was located at about the 0.44c station for the 0.20c flap and at about the 0.47c station for the 0.15c flap. With both gaps open, the location shifted about 0.03c rearward for each flap. The data of reference 5 indicate that the aerodynamic center of the lift due to deflection of a sealed 0.30c flap is at the 0.40c station. For double-flap arrangements, the aerodynamic center should be between that for the 0.20c single flap and that for the 0.15c single flap at a distance proportional to the amount of the total lift contributed by each flap. An inspection of figure 4 shows that, for $d\delta_2/d\delta_1 = 1$ and 2, the aerodynamic center lies at about 0.45c in both cases. It should be remembered that this aerodynamic center is a function of aspect ratio and will move toward the trailing edge as the aspect ratio is decreased.

CONCLUSIONS

Tests have been made of the NACA 0009 airfoil with a double plain flap that consisted of a plain forward flap

having a chord 20 percent of the airfoil chord (0.20c) and a 0.15c plain rearward flap. A comparison of the results of the present tests and of previously published tests with the characteristics of conventional control surfaces indicated the following general conclusions:

1. A 0.20c single or a 0.20c double plain flap deflected 60° positively at zero and positive angles of attack was capable of producing lift as great or greater than a 0.50c plain flap deflected 30° . At large negative angles of attack, these small-chord flaps were capable of producing as much positive lift as a 0.50c plain flap deflected 17° .

2. A 0.20c double plain flap was capable of producing adequate lift for use as a rudder or as an aileron. For use as an elevator, however, a double flap of slightly larger chord may be required if more than 30° deflection of a conventional 0.30c elevator or more than 17° deflection of a conventional 0.50c elevator is required to land the airplane.

3. When adequately balanced, small-chord double flaps of large lift effectiveness should be desirable for use as ailerons because the aileron span may be reduced and thereby may permit the use of larger-span high-lift devices.

4. With a 0.20c double plain flap, a lift effectiveness per unit stick (or pedal) deflection equal to that of a 0.50c single plain flap can be obtained by adjusting the rate of flap deflection with stick (or pedal) deflection. Under these conditions, the 0.20c double plain flap had a rate of change of stick hinge moment with angle of attack that was about one-sixteenth that for the 0.50c flap and a rate of change of stick hinge moment with stick (or pedal) deflection that was less than one-fourth that for the 0.50c flap.

5. With controls free, the slope of the lift curve for a control surface having a 0.20c single or a 0.20c double plain flap is more than twice that for a control surface having a 0.50c single plain flap. The control-free stability of the airplane will vary accordingly.

6. Although the stick hinge moments of small-chord double plain flaps are much less than those of large-chord single flaps, they are not small enough for use as control surfaces on large high-speed airplanes.

7. In order to function efficiently, a double-flap control surface must have sealed gaps and the rearward flap must have a chord that is a large percentage of the chord of the forward flap.

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TABLE I
PARAMETER VALUES FOR NACA 0009 AIRFOIL WITH A 0.20c PLAIN
FORWARD FLAP AND A 0.15c PLAIN REARWARD FLAP

Forward-flap nose gap	Rearward- flap nose gap	$\left(\frac{\partial a_0}{\partial \delta_1}\right)_{c_l, \delta_2}$	$\left(\frac{\partial c_{h1}}{\partial a_0}\right)_{\delta_1, \delta_2}$	$\left(\frac{\partial c_{h1}}{\partial \delta_1}\right)_{a_0, \delta_2}$	$\left(\frac{\partial c_{h1}}{\partial \delta_2}\right)_{a_0, \delta_1}$	$\left(\frac{\partial c_m}{\partial c_l}\right)_{a_0, \delta_2}$	$\left(\frac{\partial c_l}{\partial a_0}\right)_{\delta_1, \delta_2}$
0.005c	0.005c	-0.30	-0.0050	-0.0108	-0.0126	-0.225	0.092
.005c	Sealed	-.38	-.0053	-.0116	-----	-.196	.096
Sealed	0.005c	-----	-----	-----	-----	-----	.096
Sealed	Sealed	-.43	-.0048	-.0118	-----	-.194	.098

Forward-flap nose gap	Rearward- flap nose gap	$\left(\frac{\partial a_0}{\partial \delta_2}\right)_{c_l, \delta_1}$	$\left(\frac{\partial c_{h2}}{\partial a_0}\right)_{\delta_1, \delta_2}$	$\left(\frac{\partial c_{h2}}{\partial \delta_2}\right)_{a_0, \delta_1}$	$\left(\frac{\partial c_{h2}}{\partial \delta_1}\right)_{a_0, \delta_2}$	$\left(\frac{\partial c_m}{\partial c_l}\right)_{a_0, \delta_1}$	$\left(\frac{\partial c_m}{\partial c_l}\right)_{\delta_1, \delta_2}$
0.005c	0.005c	-0.25	-0.0039	-0.0105	-0.0075	-0.245	0.020
.005c	Sealed	-----	-----	-----	-----	-----	.016
Sealed	0.005c	-.26	-.0038	-.0082	-----	-.218	.017
Sealed	Sealed	-.40	-.0033	-.0100	-----	-.218	.016

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TABLE II
COMPUTED CHARACTERISTICS OF SINGLE- AND DOUBLE-FLAP CONTROL
SYSTEMS ON AN NACA 0009 AIRFOIL

Control arrangement				$\frac{d\delta_1}{d\delta_s}$ to give $(a_{\delta_s})_{c_l} = -0.77$	$\left(\frac{\partial c_{H_s}}{\partial \delta_s}\right)_{c_l}$	$\left(\frac{\partial c_{H_s}}{\partial c_l}\right)_{\delta}$	$\left(\frac{\partial c_{H_s}}{\partial a_0}\right)_{\delta}$	$\left(\frac{\partial c_{H_s}}{\partial \delta_s}\right)_{a_0}$	$\left(\frac{\partial c_l}{\partial a_0}\right)_{\delta}$	$\left(\frac{\partial c_l}{\partial a_0}\right)_{free}$
c_1/c	c_2/c	$\frac{d\delta_2}{d\delta_1}$	Gap							
0.50	----	---	Sealed	1.00	-0.00159	-0.03300	-0.00313	-0.00400	0.095	0.038
.50	0.15	1	--do--	.66	-.00177	-.02220	-.00211	-.00339	.095	.047
.50	.15	2	--do--	.52	-.00218	-.01820	-.00173	-.00351	.095	.059
.50	----	---	--do--	1.35	-.00142	-.00958	-.00091	-.00214	.095	.064
.30	.09	1	--do--	.96	-.00155	-.00706	-.00067	-.00207	.095	.071
.30	.09	2	--do--	.76	-.00173	-.00570	-.00054	-.00215	.095	.078
.20	----	---	--do--	1.79	-.00125	-.00340	-.00032	-.00148	.098	.081
.20	.15	1	--do--	.72	-.00079	-.00210	-.00021	-.00093	.098	.081
.20	.15	2	--do--	.54	-.00080	-.00201	-.00020	-.00095	.098	.082
.30	----	---	0.005c	1.42	-.00166	-.00900	-.00086	-.00232	.095	.067
.20	----	---	.005c	1.71	-.00110	-.00379	-.00036	-.00138	.096	.077
.20	.15	1	.005c	1.40	-.00214	-.00432	-.00040	-.00245	.092	.081
.20	.15	2	.005c	1.01	-.00244	-.00400	-.00037	-.00275	.092	.082
.20	.15	3	.005c	.80	-.00266	-.00390	-.00036	-.00294	.092	.083

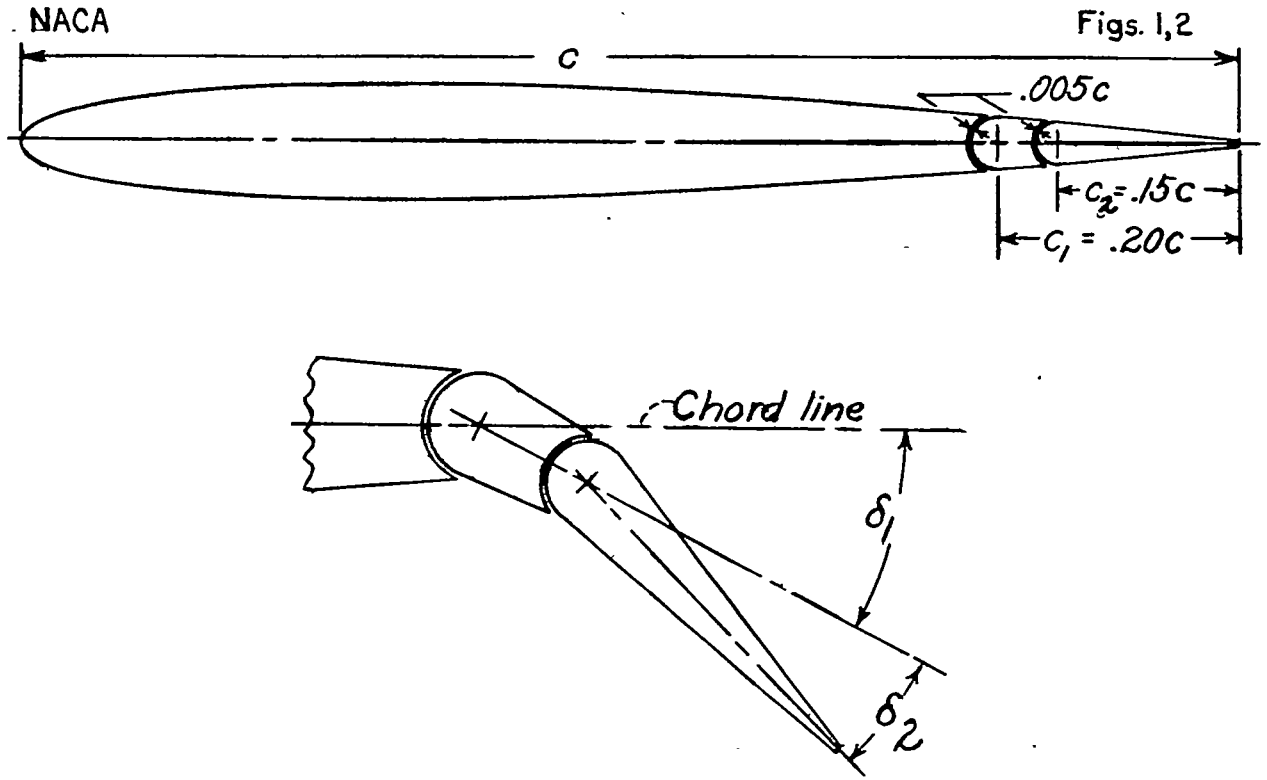


Figure 1.- Two-foot-chord NACA 0009 airfoil with a $0.20c$ double plain flap.

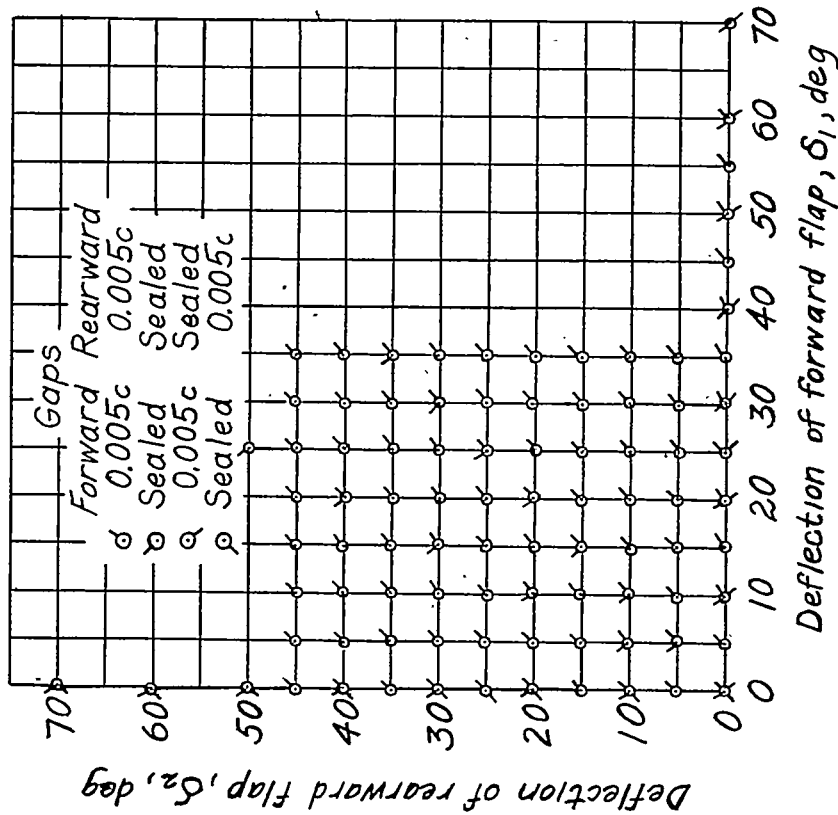


Figure 2.- Flap deflections used in tests of the NACA 0009 airfoil with a $0.20c$ double plain flap.

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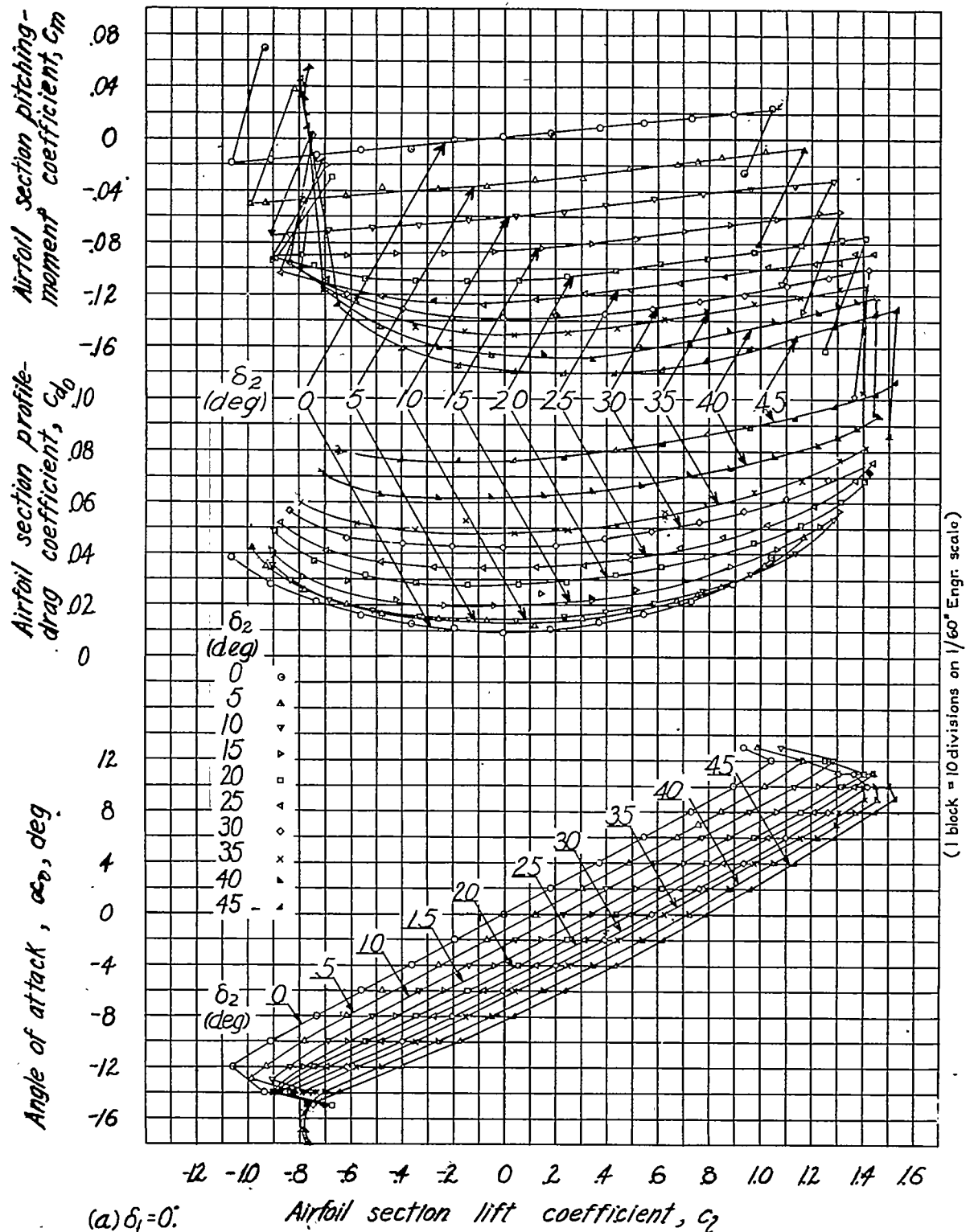
(a) $\delta_1 = 0^\circ$.Airfoil section lift coefficient, c_l

Fig. 3(a to h) Aerodynamic section characteristics of an NACA 0009 airfoil having a 0.20c double plain flap. Forward gap, 0.005c; rearward gap, 0.005c.

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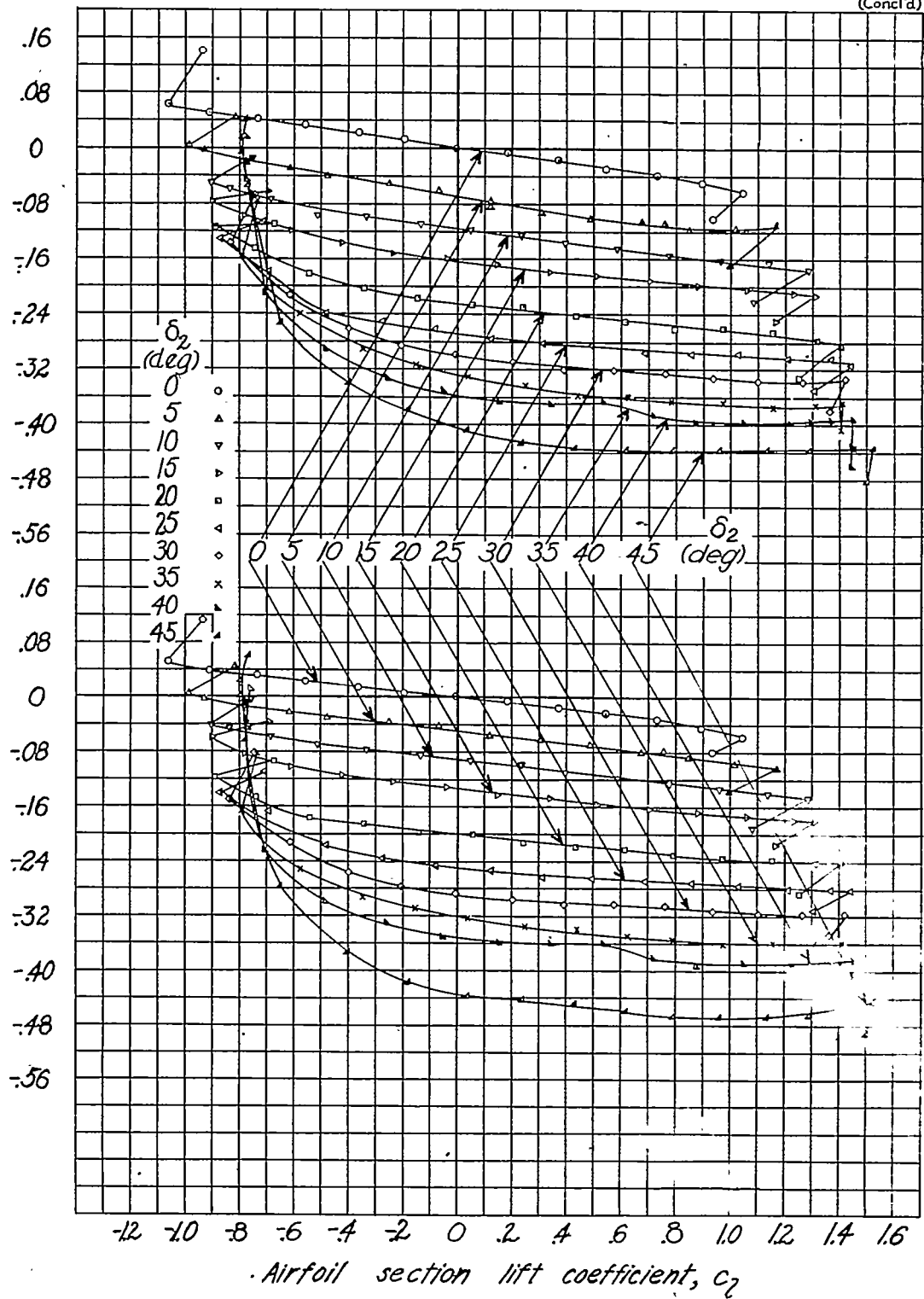
Forward-flap section hinge-moment
coefficient, Ch_1 Rearward-flap section hinge-moment
coefficient, Ch_2 (a) Concluded. $\delta_1 = 0^\circ$

Figure 3.-Continued.

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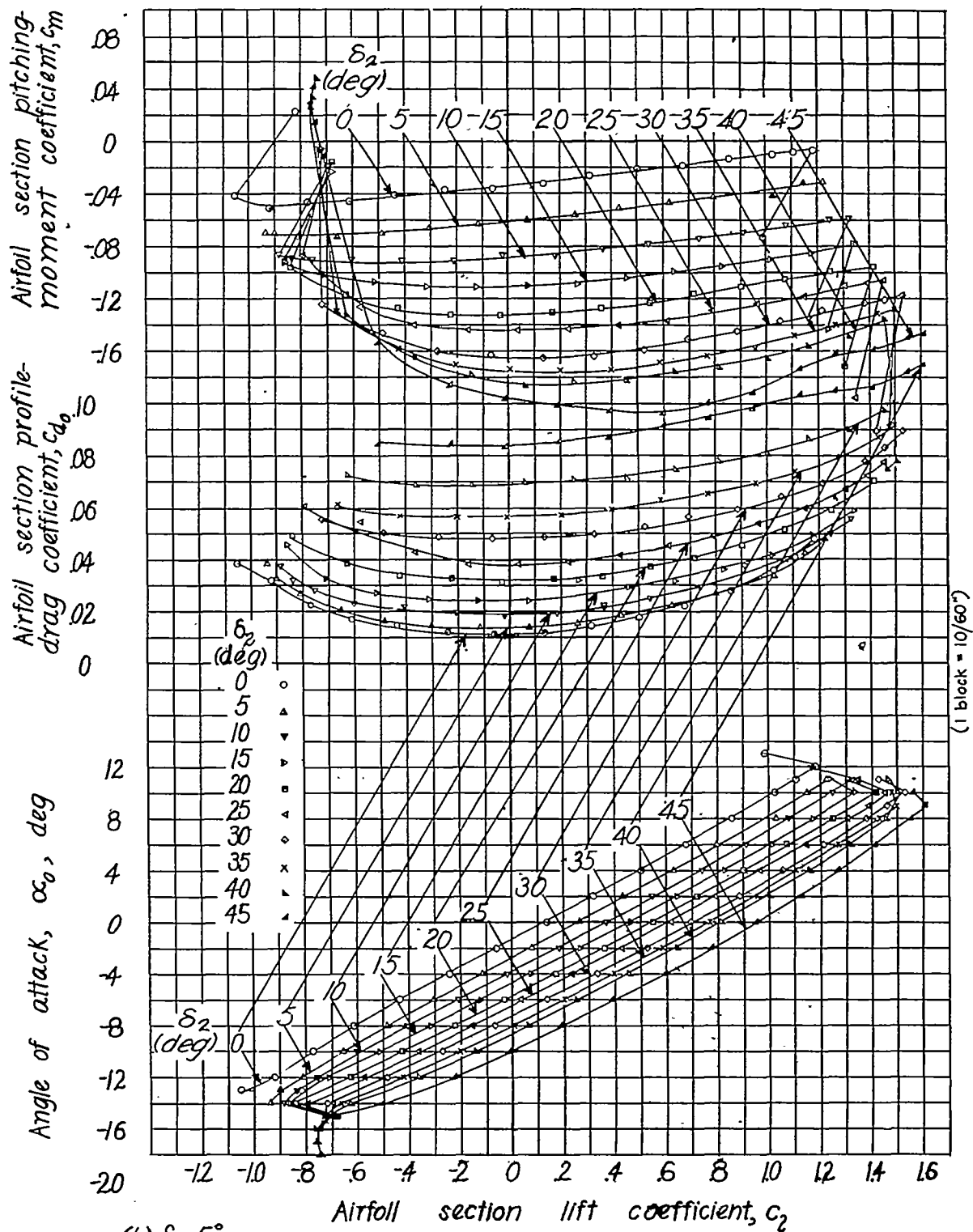
(b) $\delta_1 = 5^\circ$

Figure 3.-Continued.

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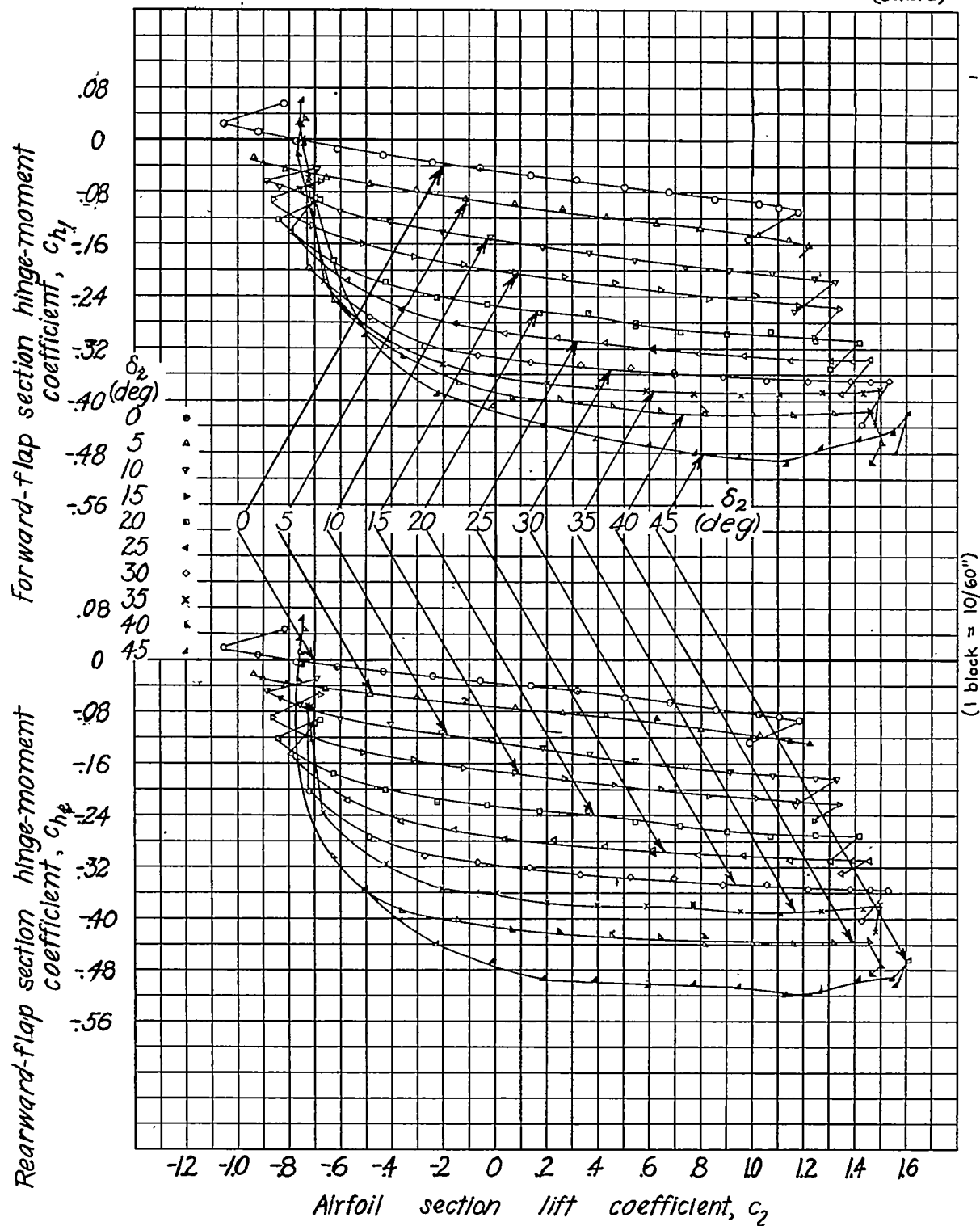
(b) Concluded. $\delta_1 = 5^\circ$

Figure 3.-Continued.

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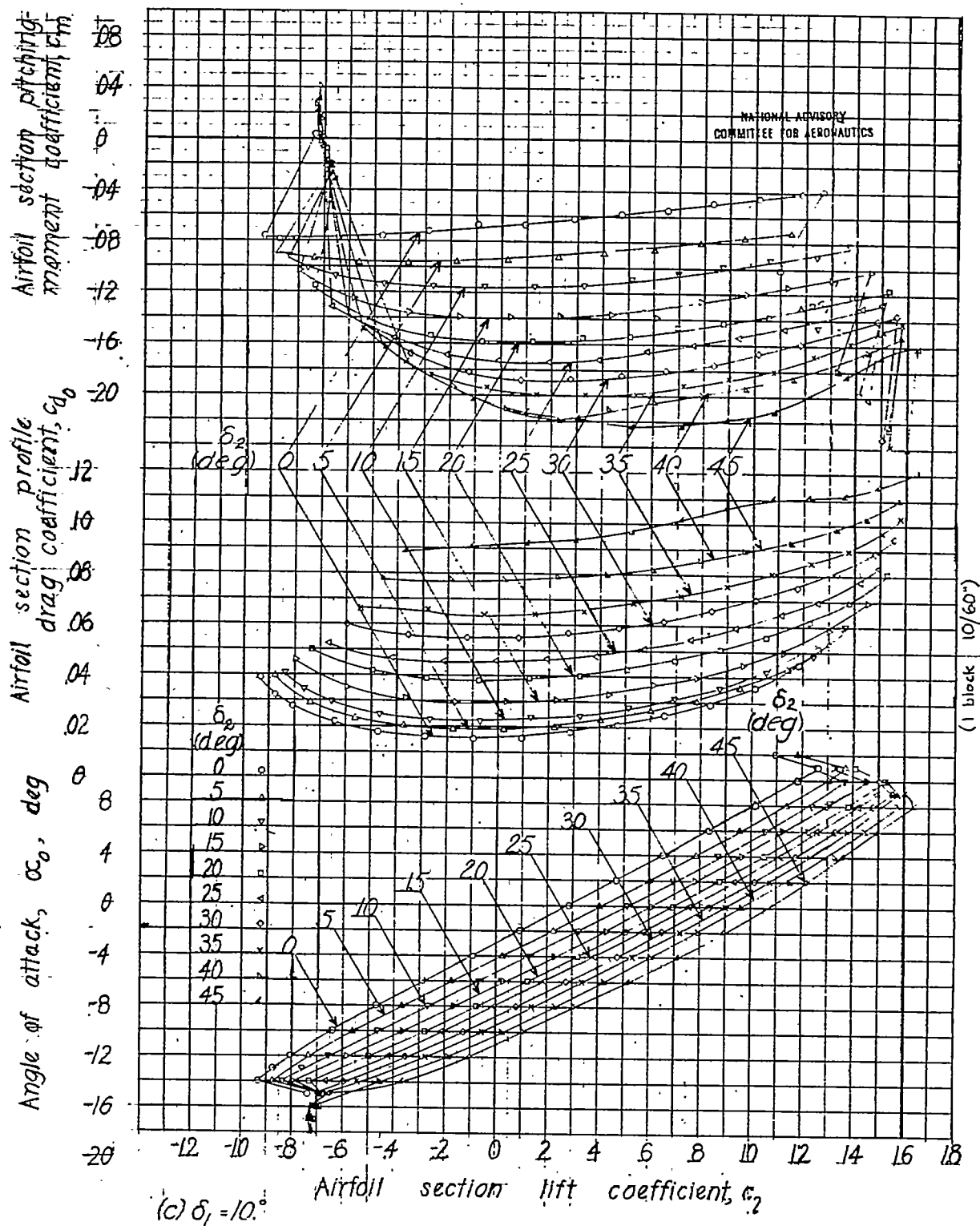


Figure 3.-Continued.

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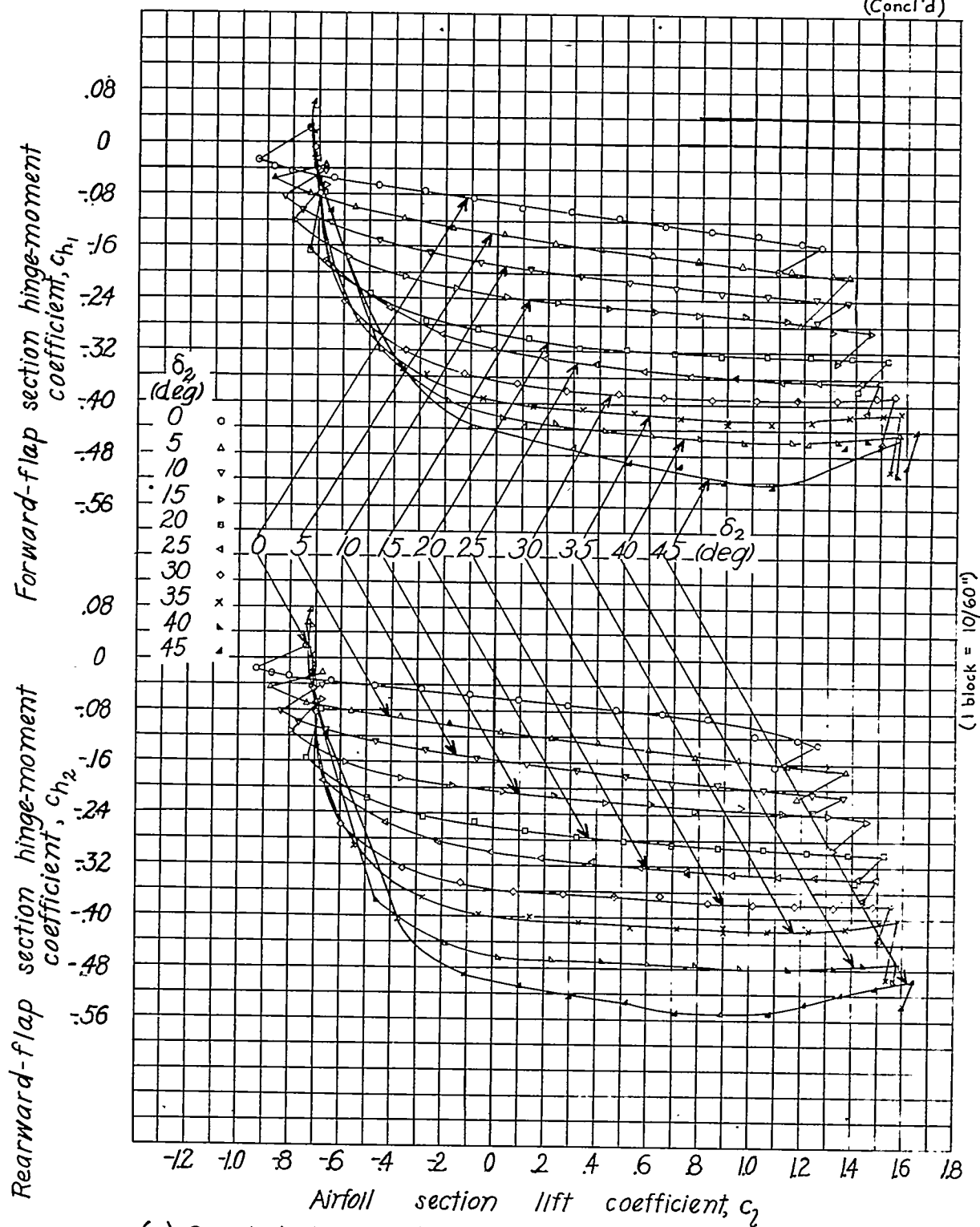
(c) Concluded. $\delta_1 = 10^\circ$

Figure 3.-Continued.

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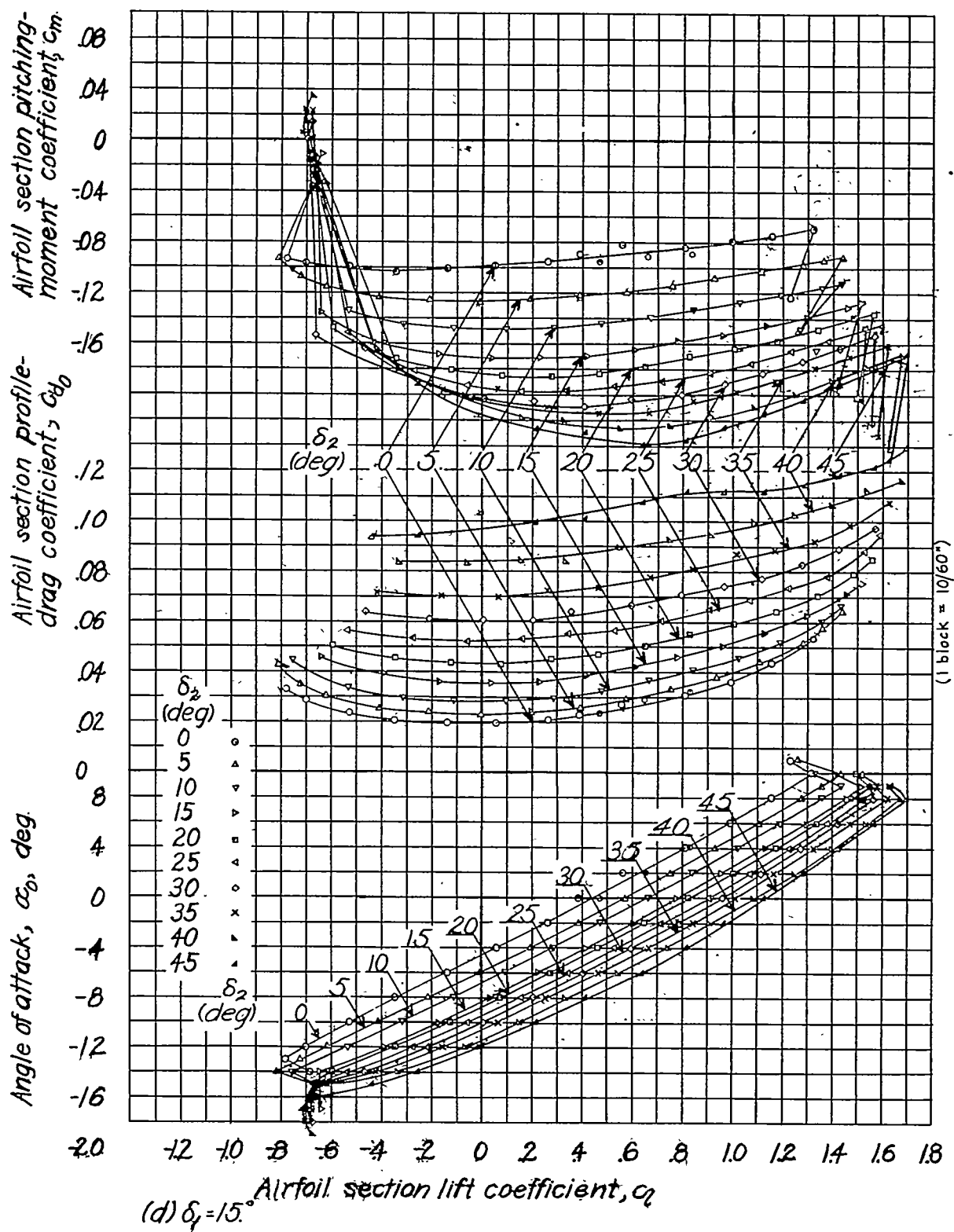
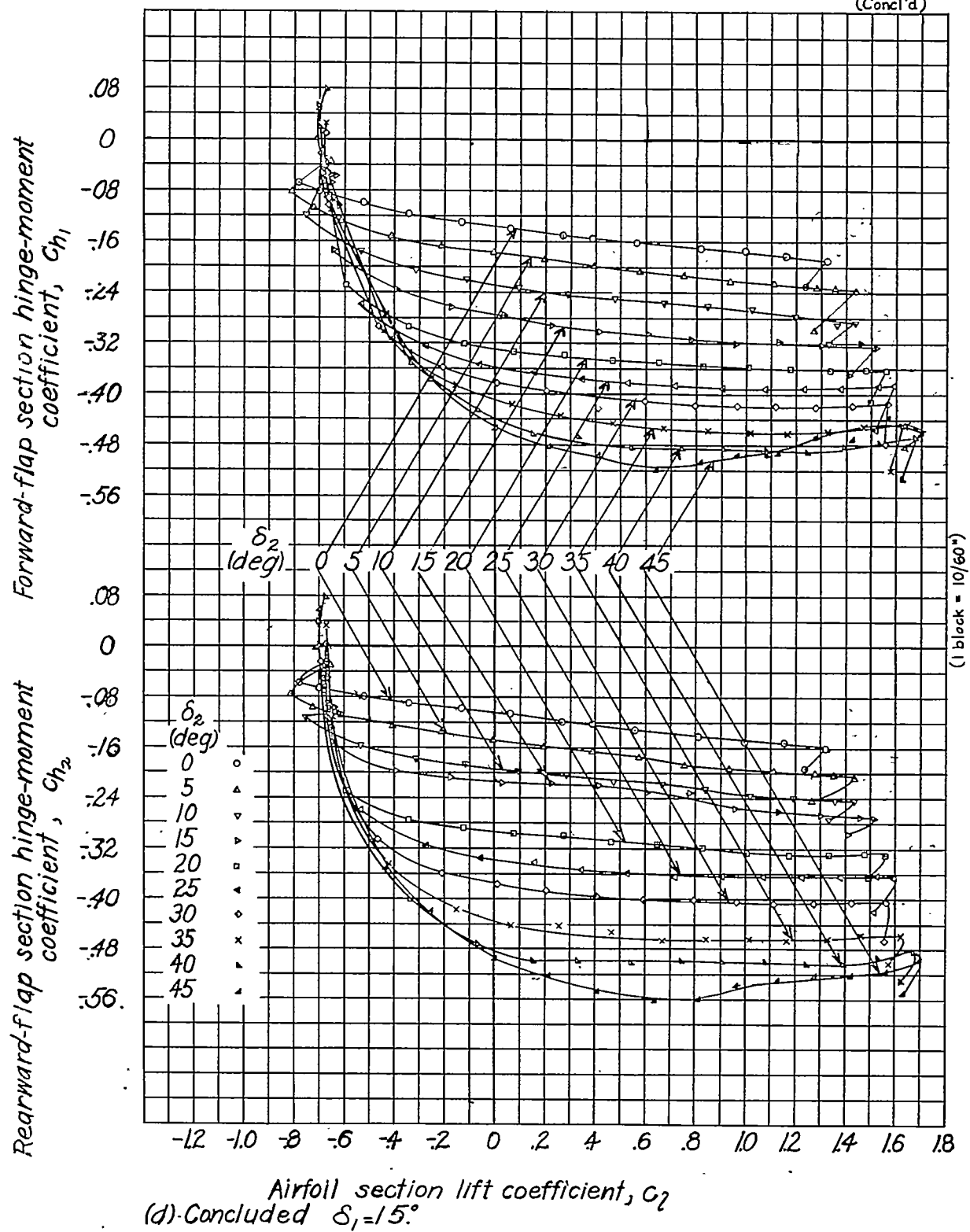


Figure 3.-Continued.

Fig. 3d
(Concl'd)

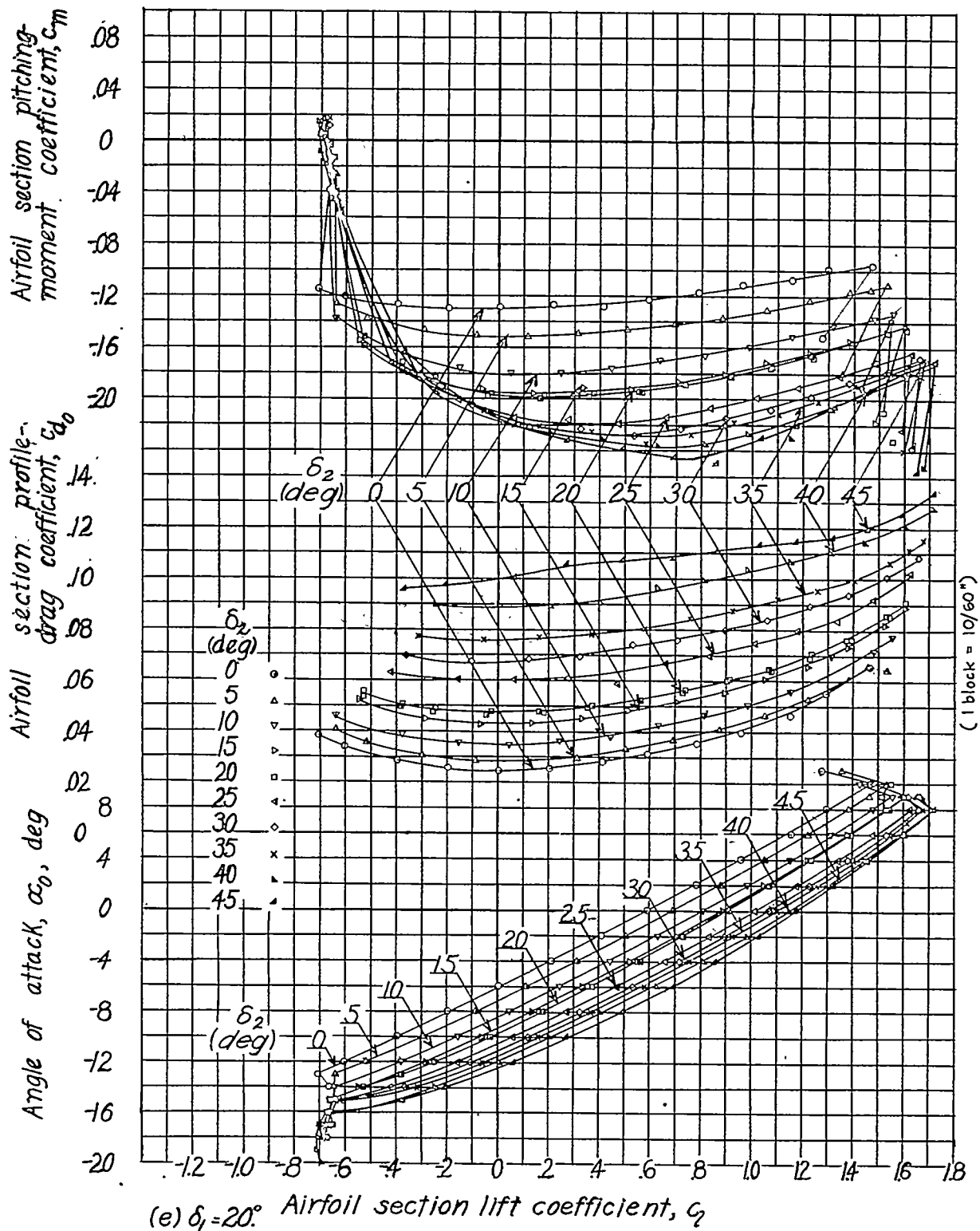
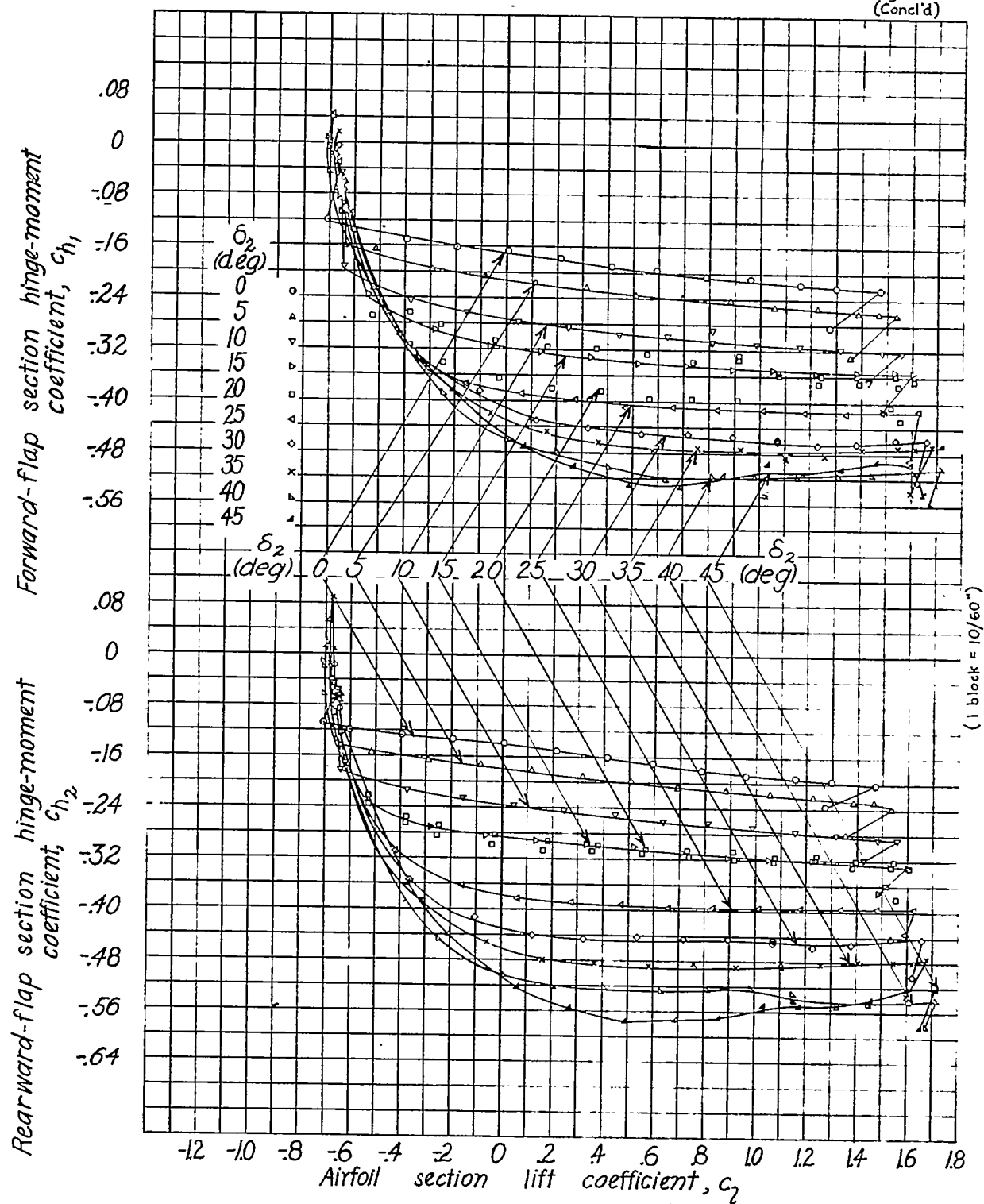


Figure 3.- Continued.



(e) Concluded. $\delta_1 = 2.0^\circ$

Figure 3.-Continued.

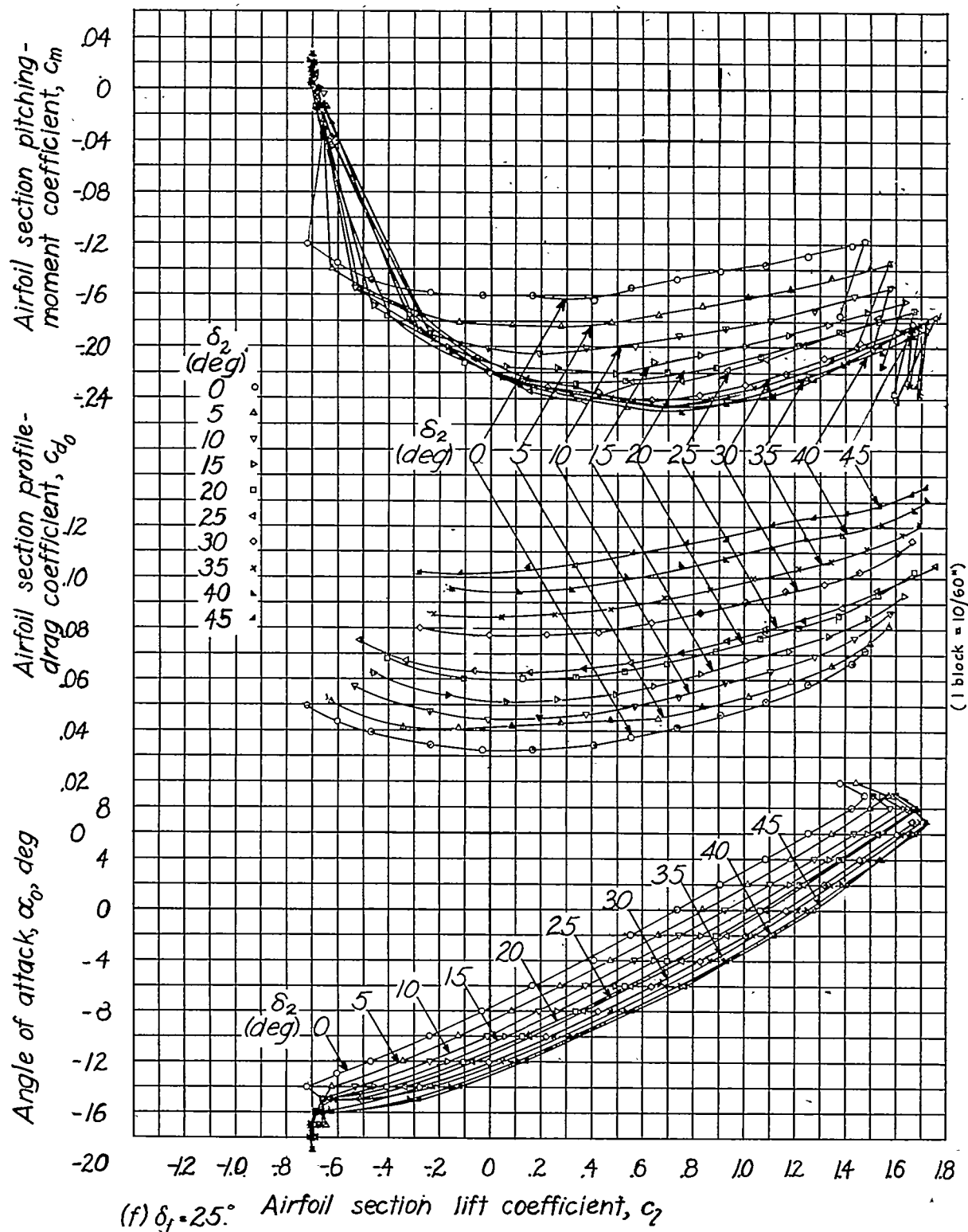


Figure 3.-Continued.

Fig. 3f
(Concl'd)

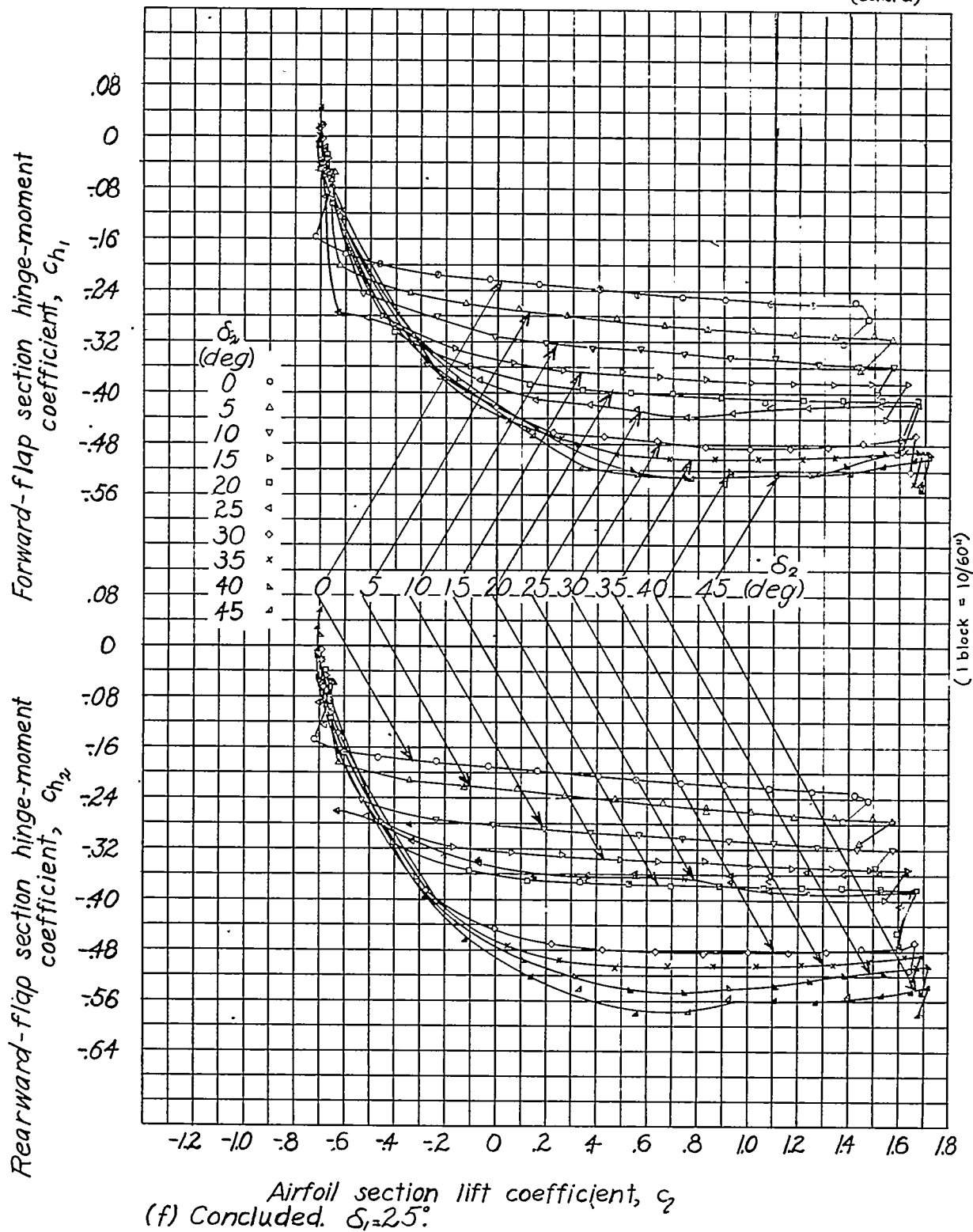


Figure 3.-Continued.

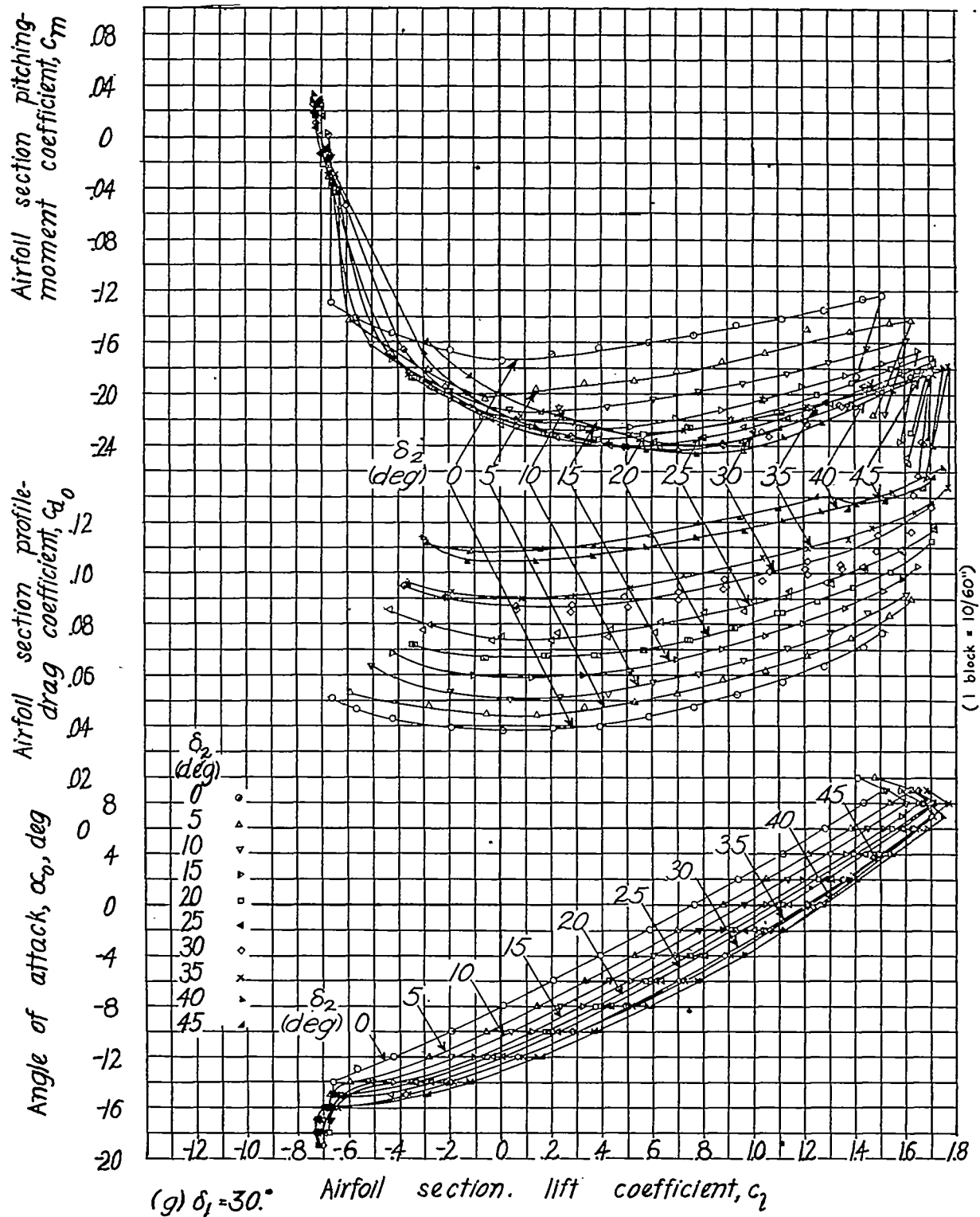


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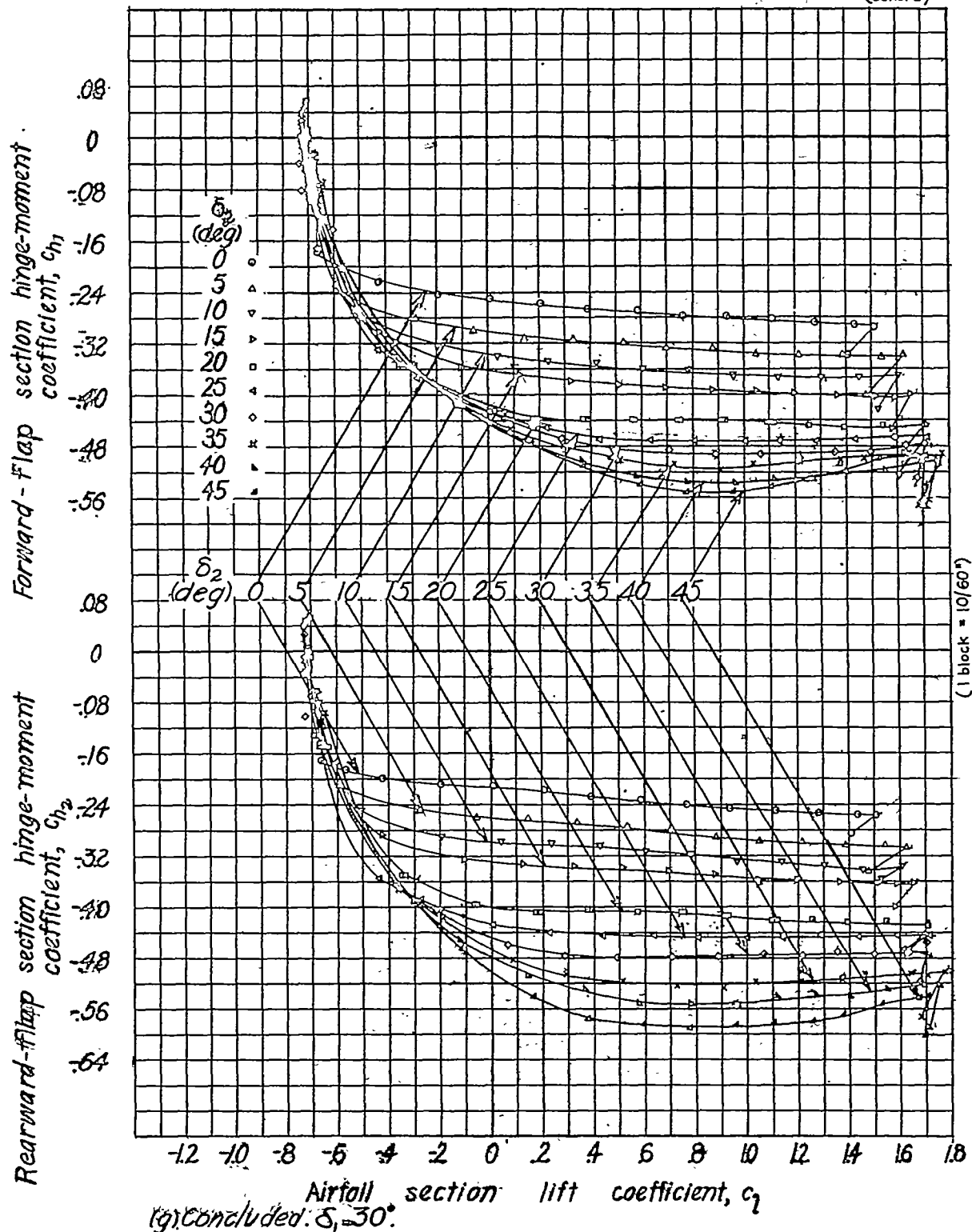


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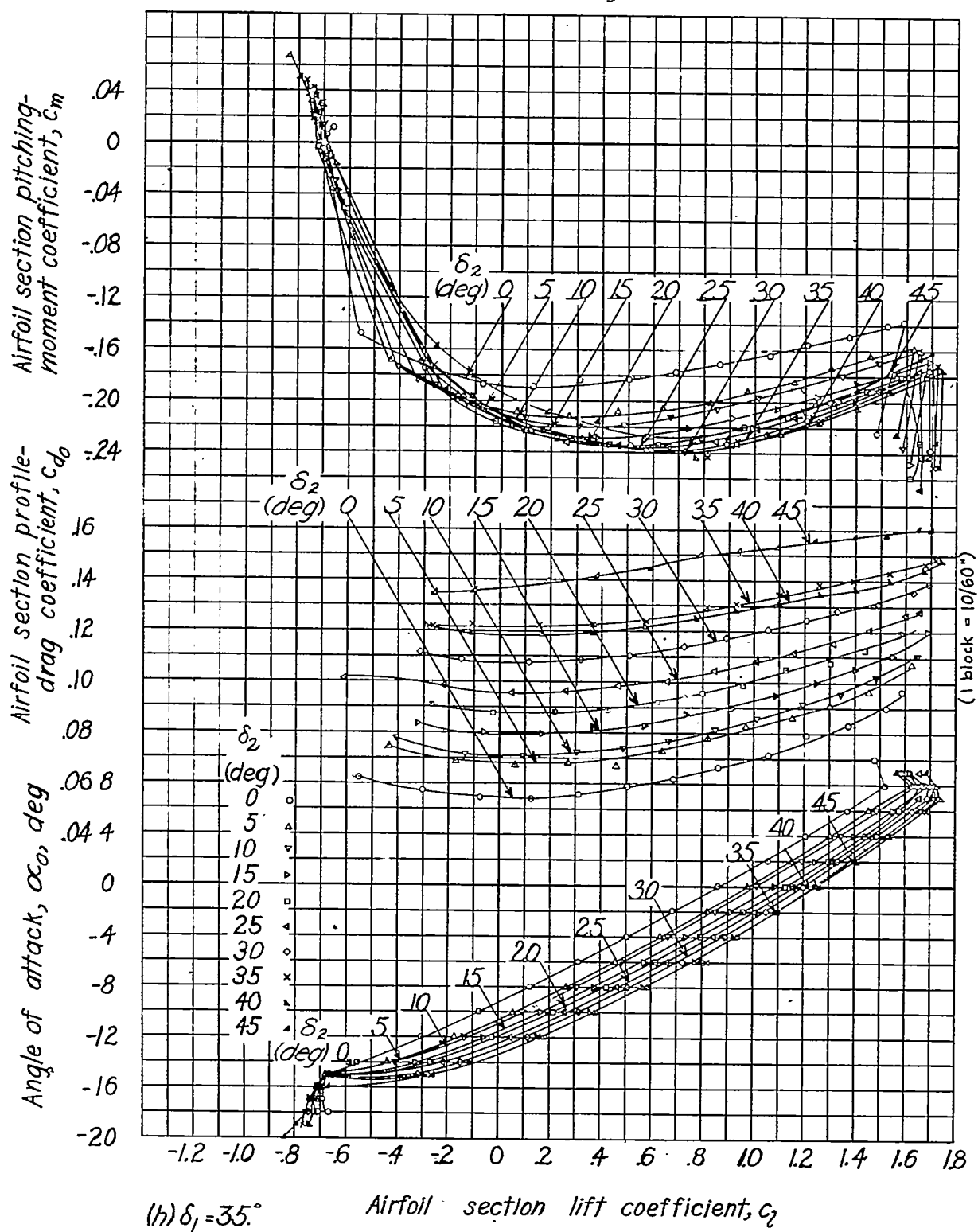


Figure 3.-Continued.

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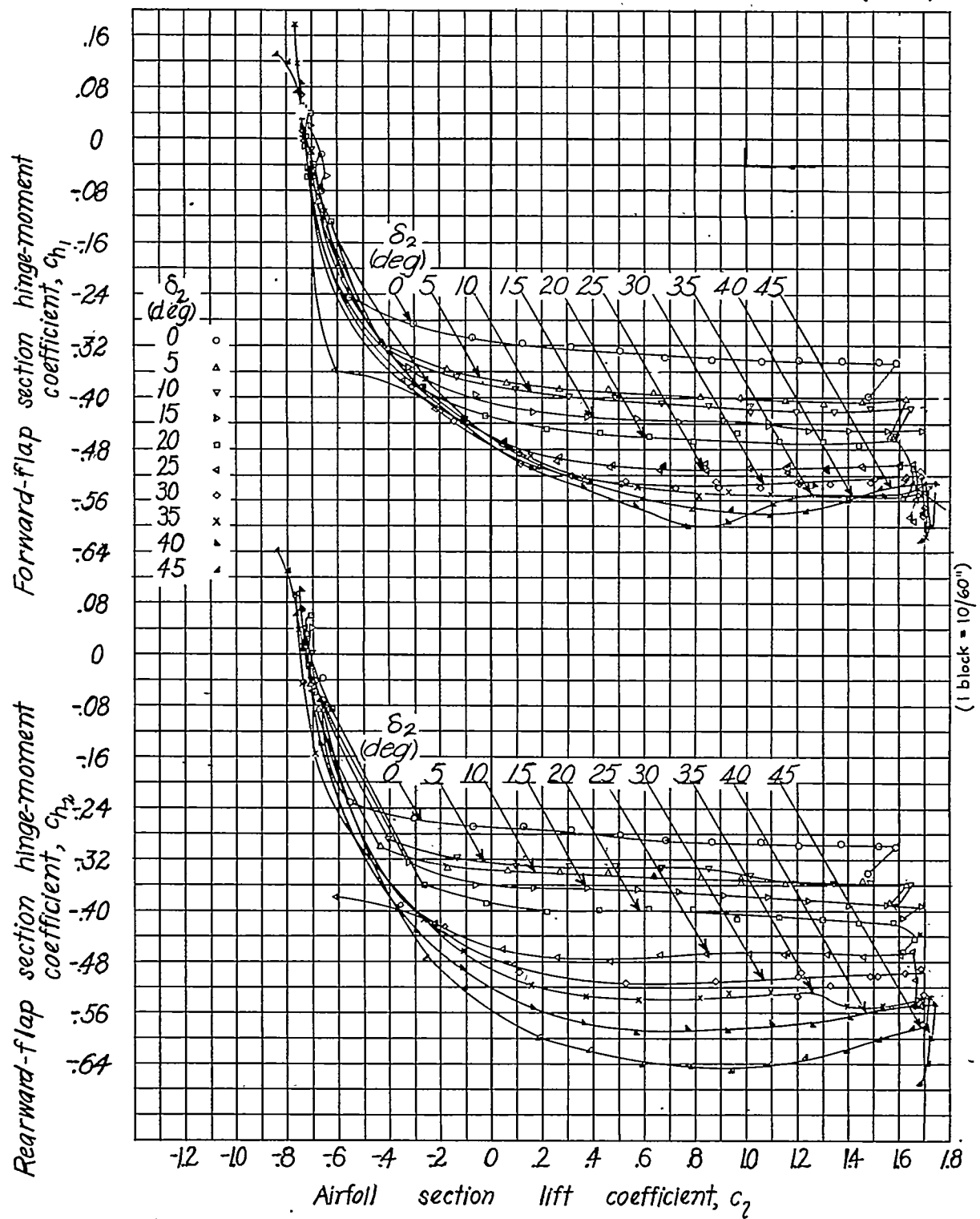
(h) Concluded. $\delta_1 = 35^\circ$.

Figure 3.-Concluded.

NACA

Fig. 4a

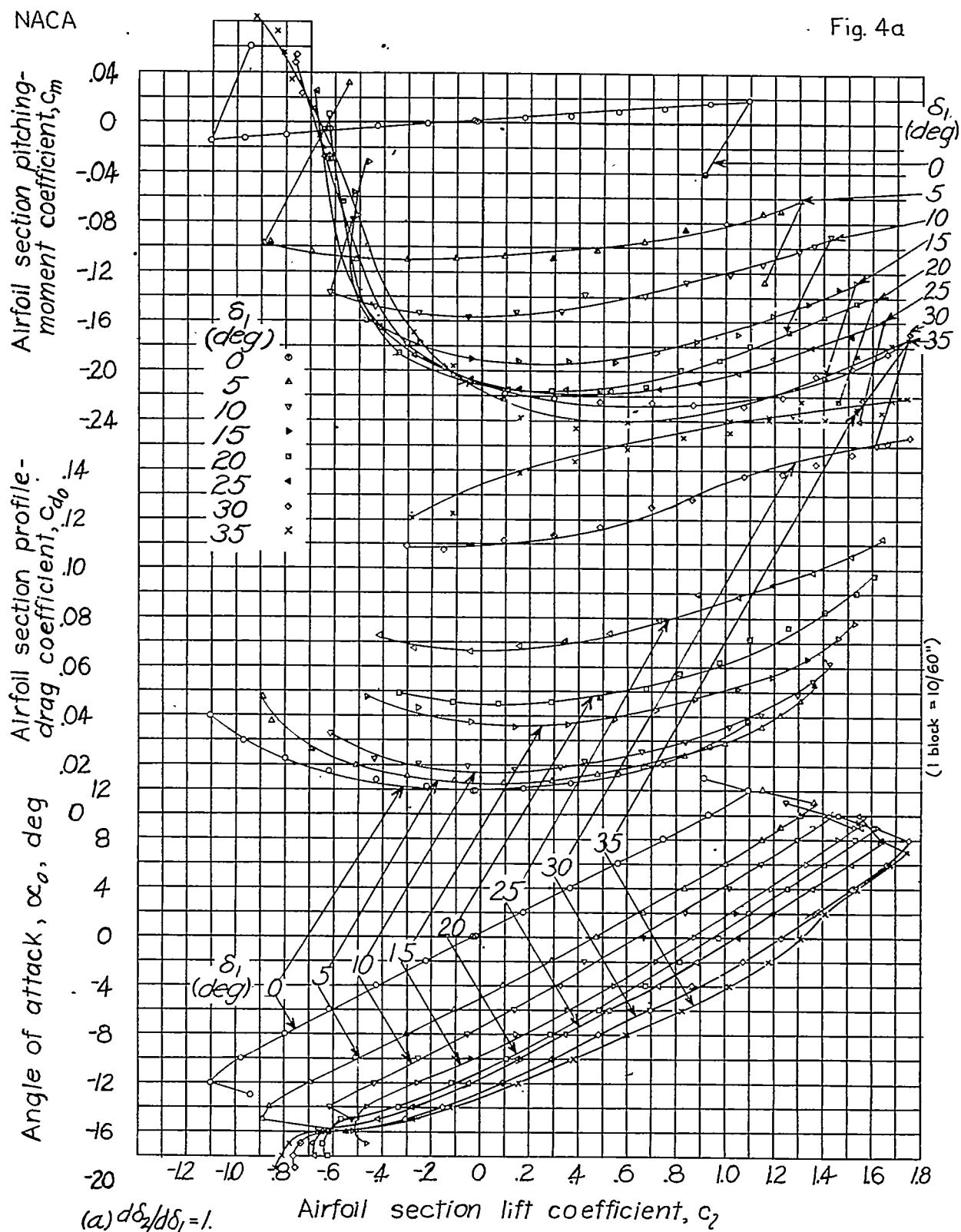


Fig. 4(a,b)-Aerodynamic section characteristics of an NACA 0009 airfoil having a 0.20c double plain flap. Forward gap, sealed; rearward gap, sealed.

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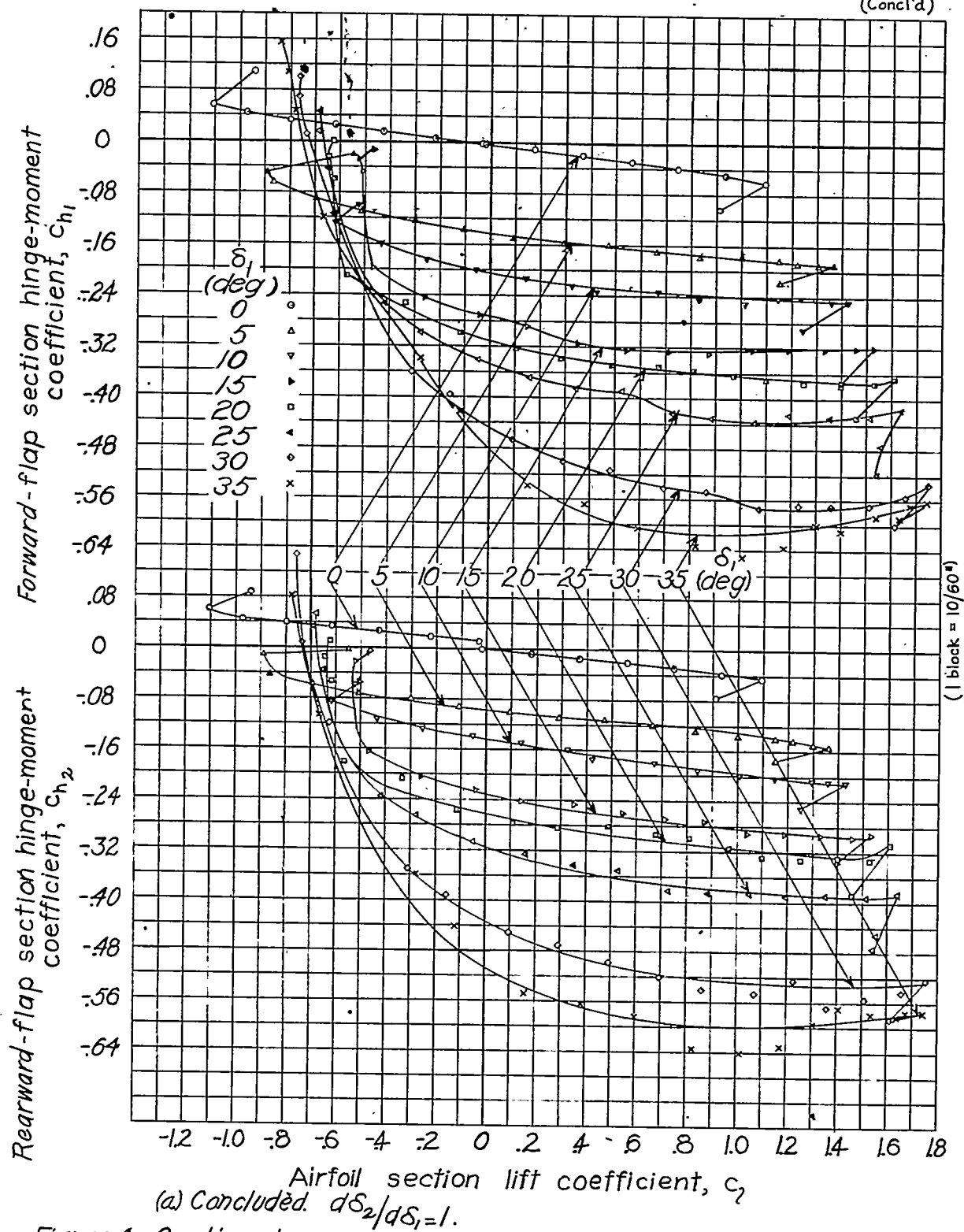


Figure 4.-Continued.

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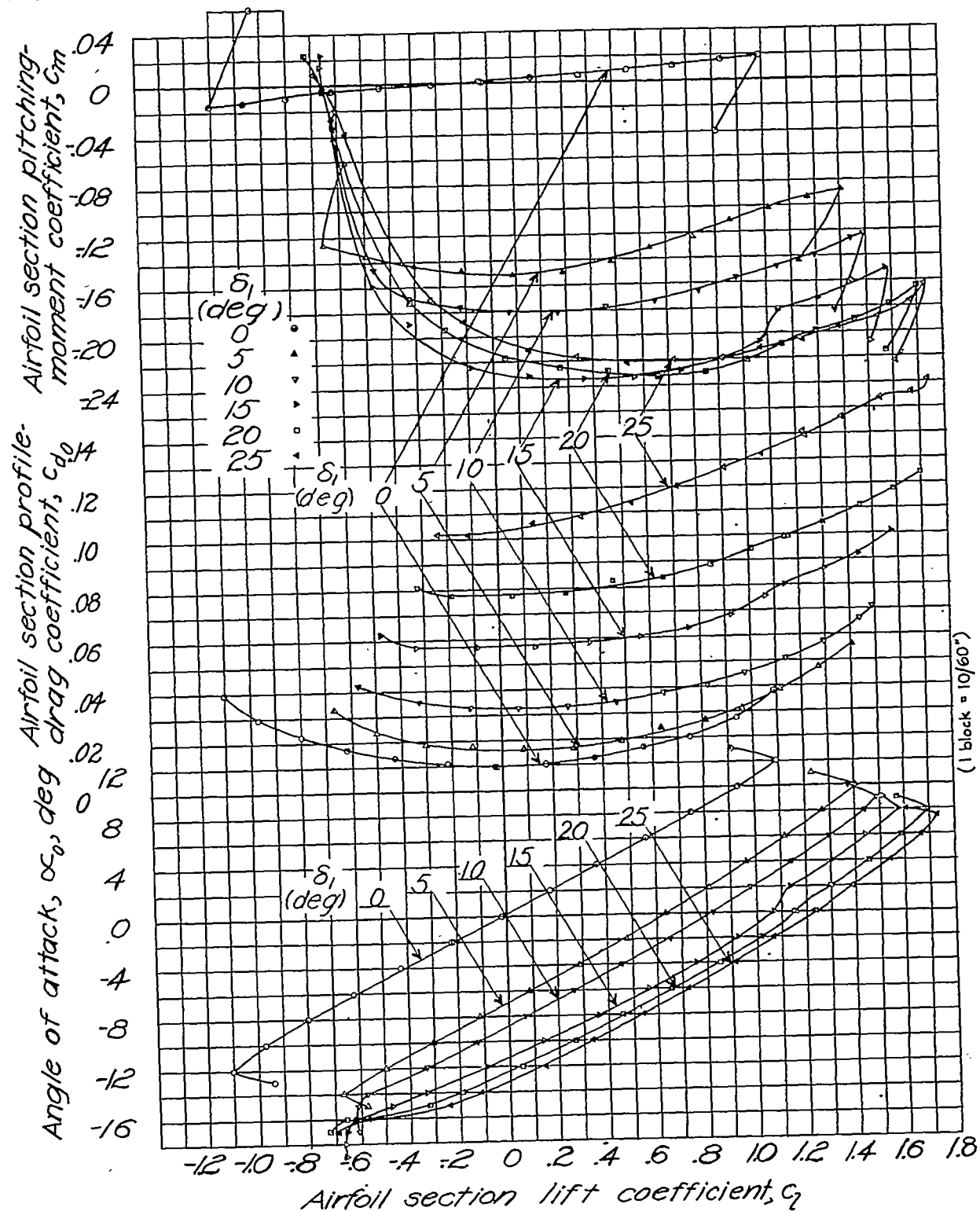
(b) $d\delta_1/d\delta_1 = 2$.

Figure 4.- Continued.

NACA

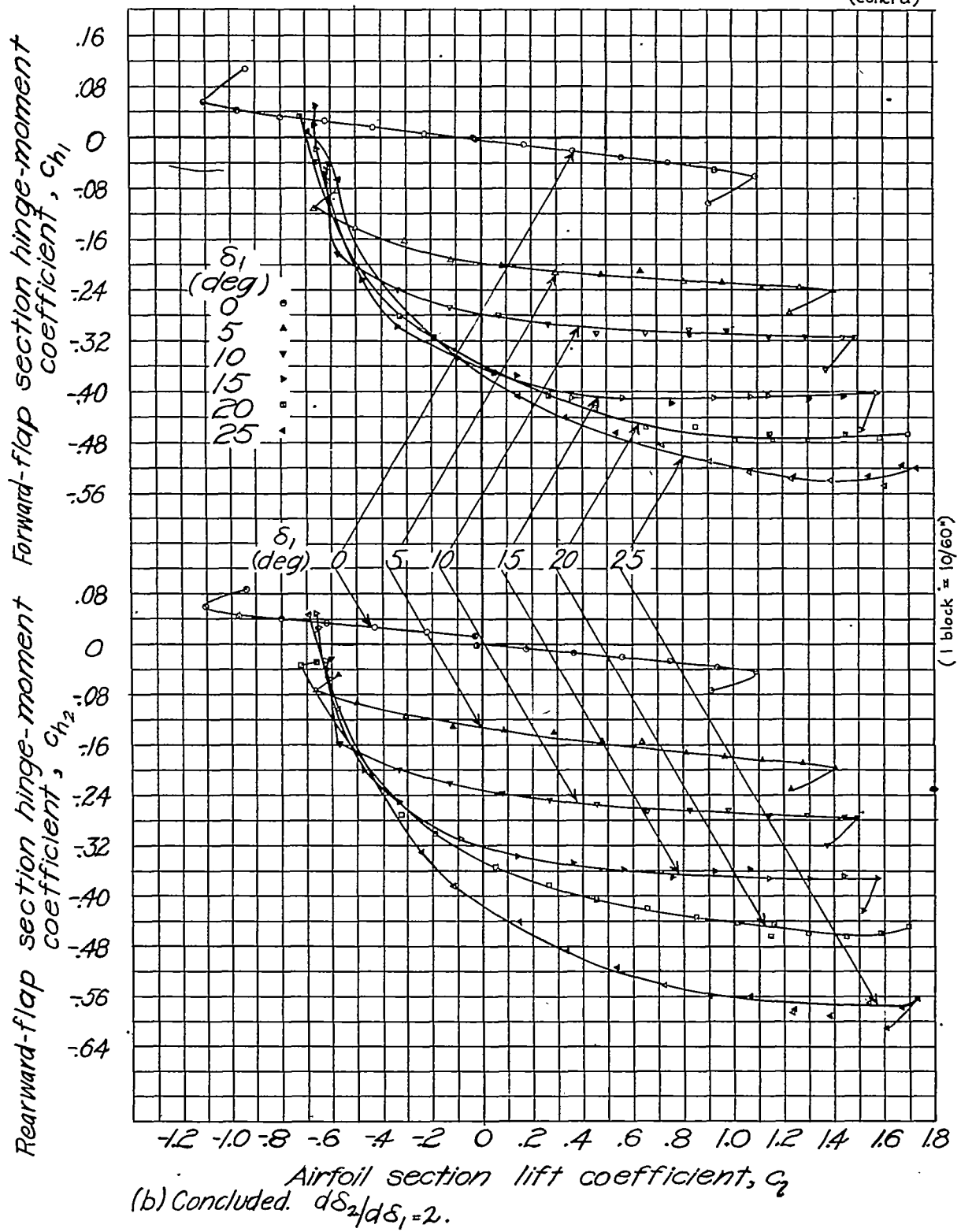
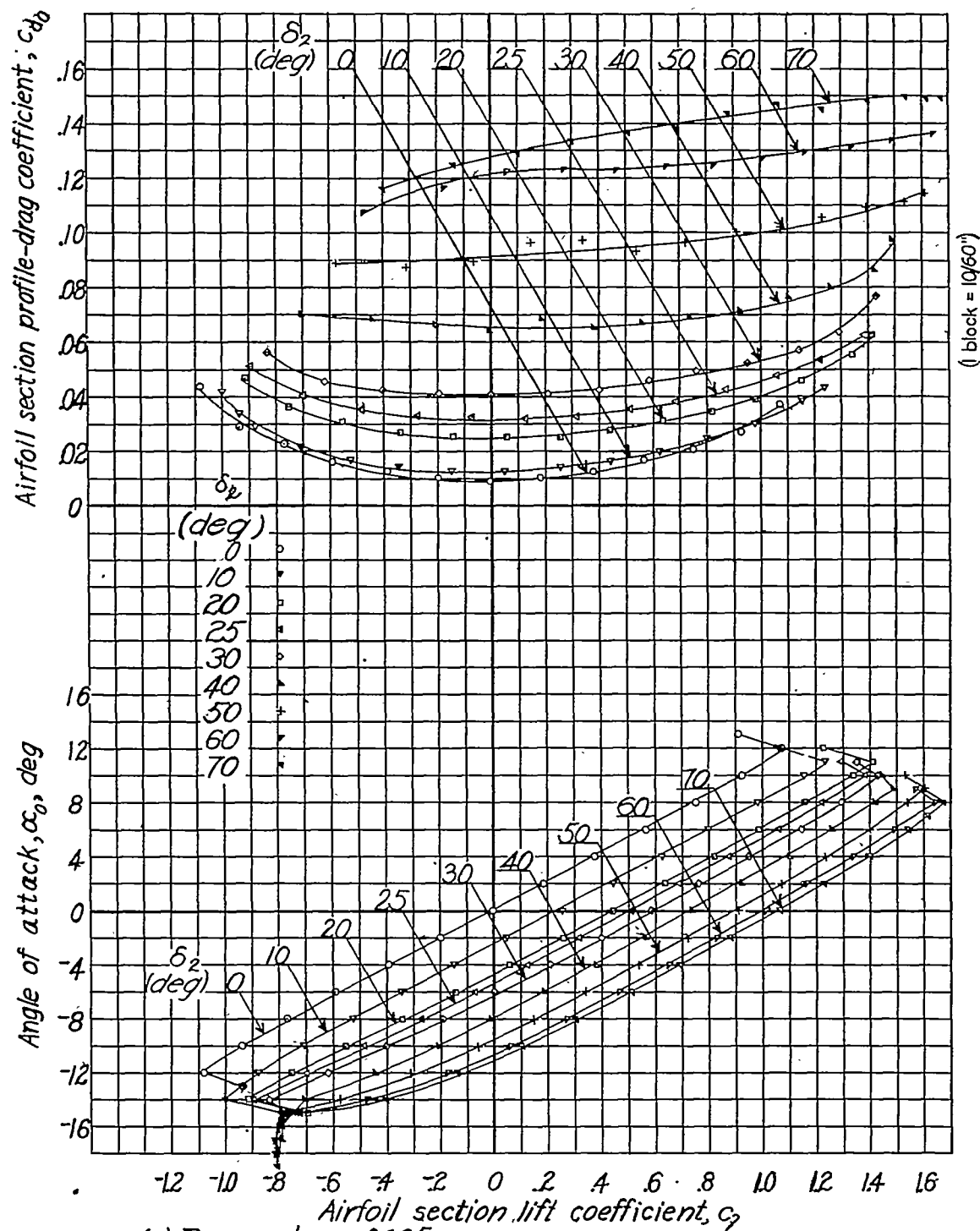
Fig. 4b
(Concl'd)

Figure 4.- Concluded.

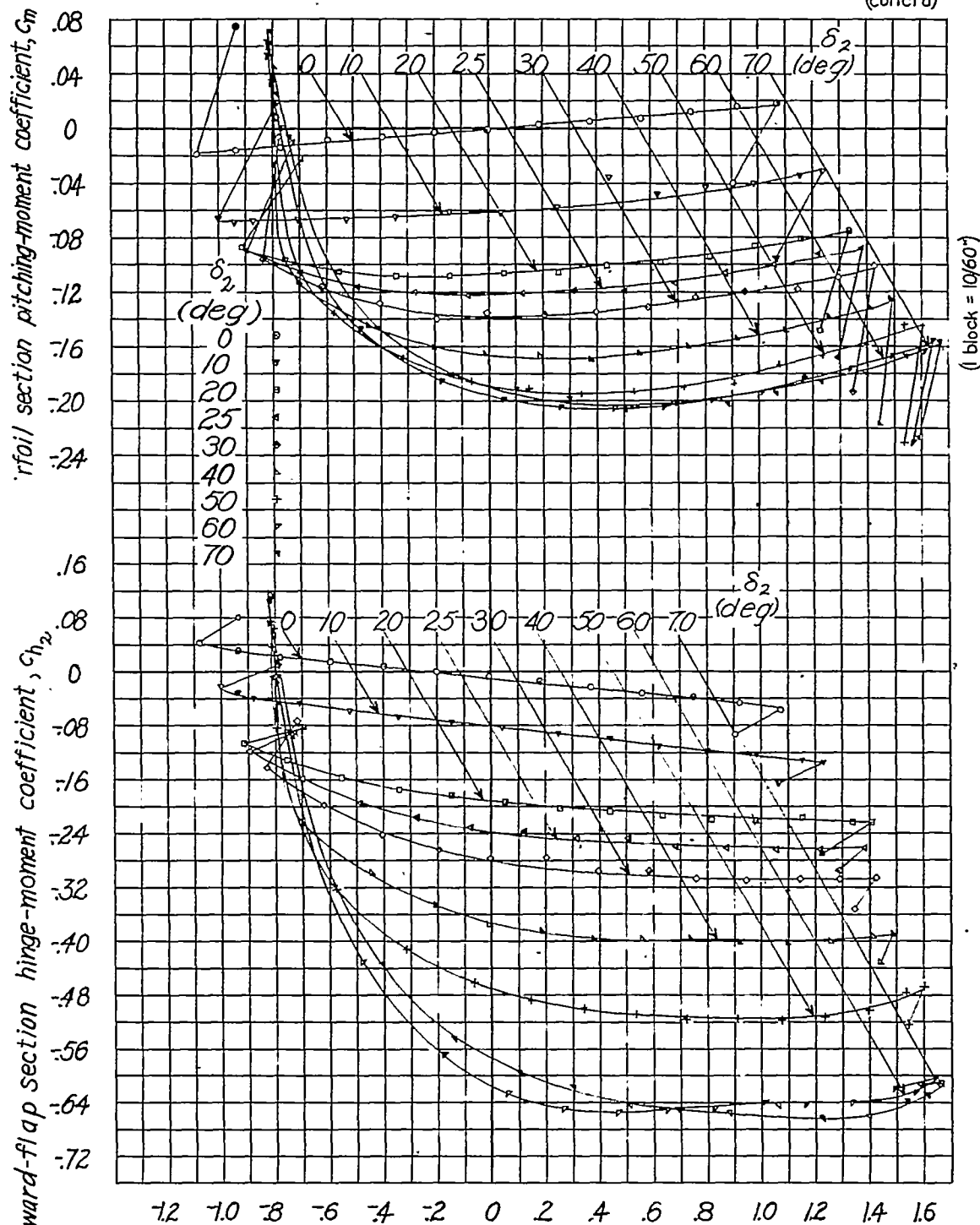
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(a) Rearward gap, 0.005c.

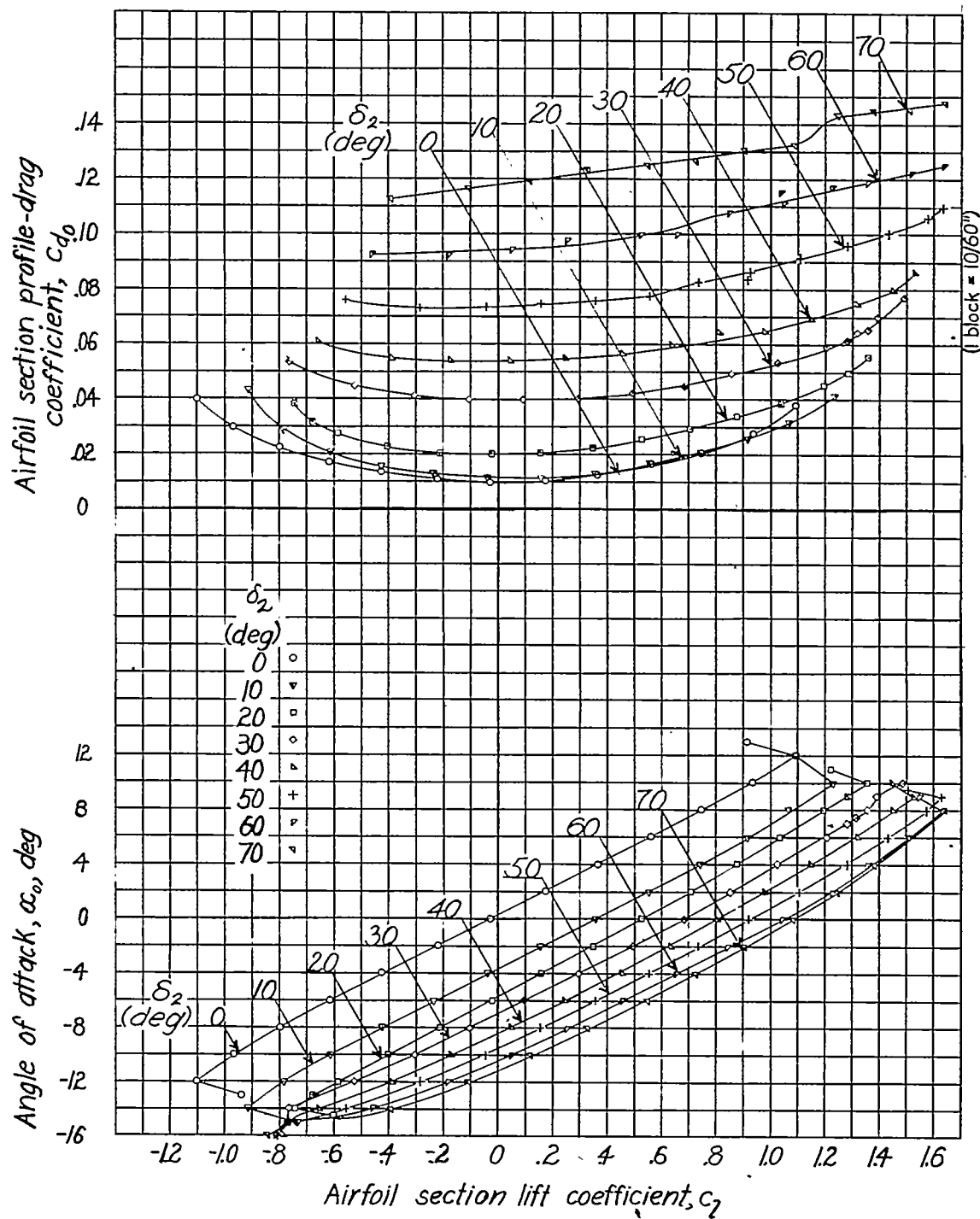
Figure 5.-Aerodynamic section characteristics of an NACA 0009 airfoil having a 0.20c double plain flap. Forward gap, sealed; $\delta_1, 0^\circ$.

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(a) Concluded. Airfoil section lift coefficient, C_l
 Rearward gap, 0.005c.

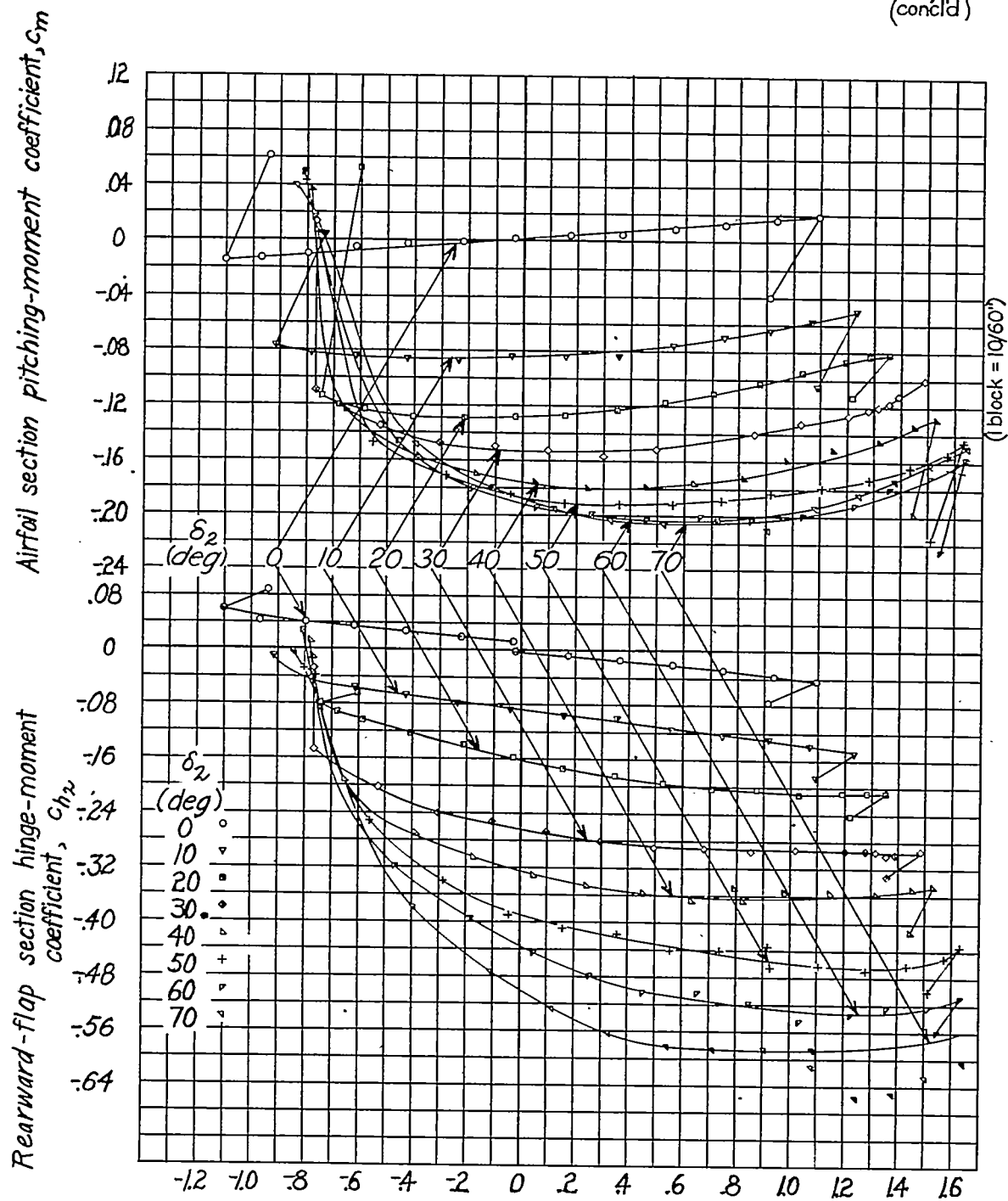
Figure 5.-Continued.



(b) Rearward gap, sealed.

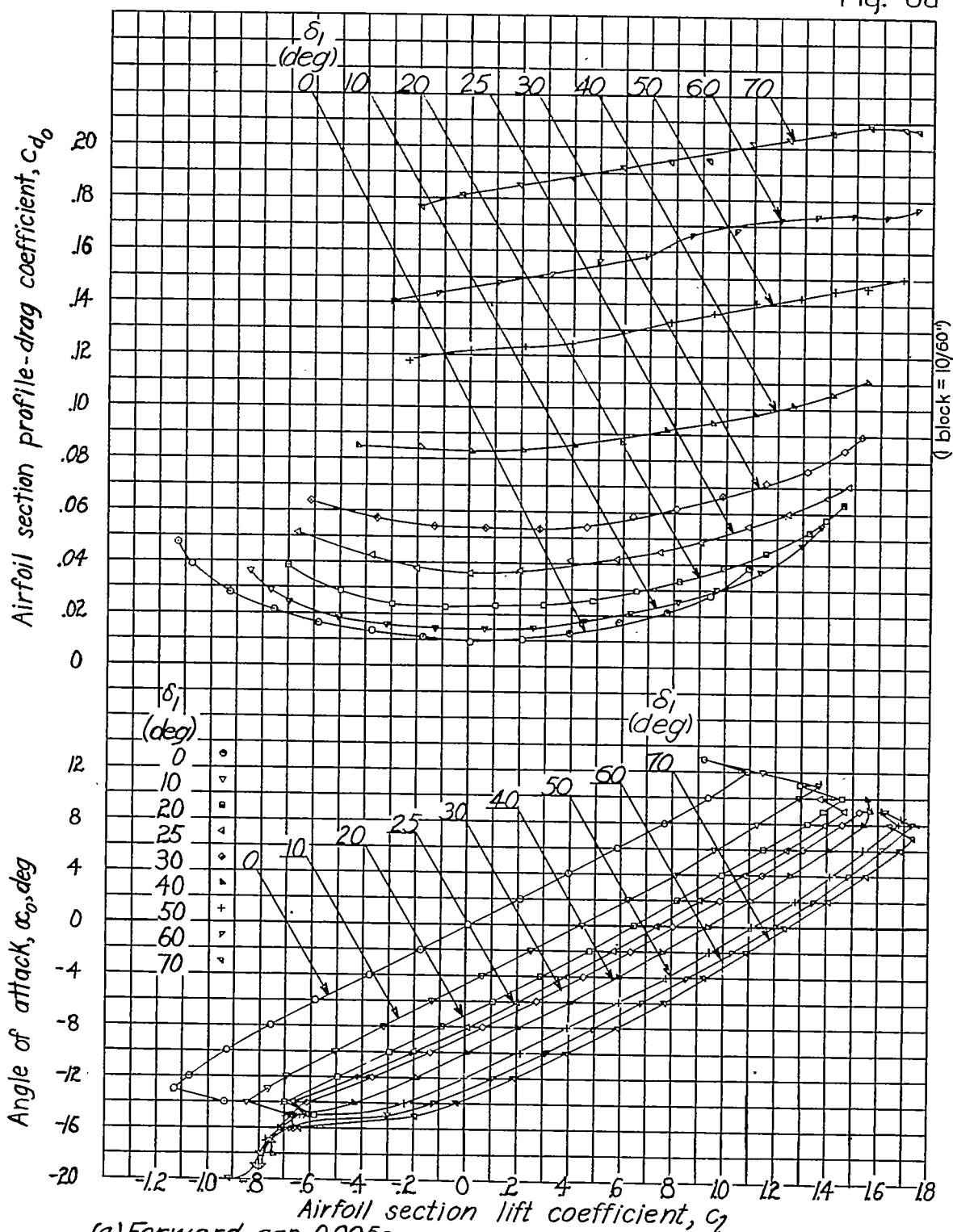
Figure 5.-Continued.

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(b) Concluded.
Figure 5.-Concluded.

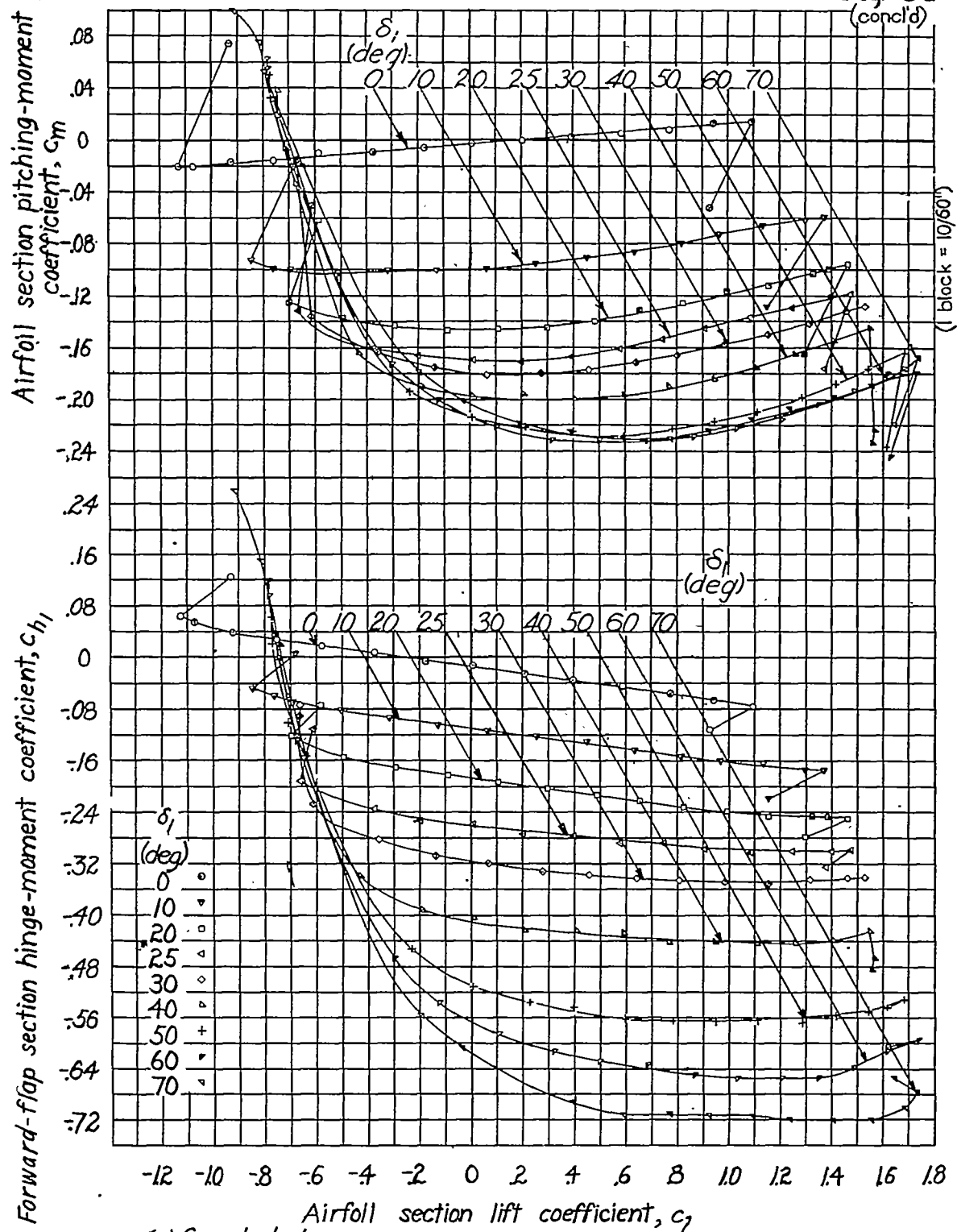
Airfoil section lift coefficient, c_l
Rearward gap, sealed.



(a) Forward gap, 0.005c.

Figure 6.-Aerodynamic section characteristics of an NACA 0009 airfoil having a 0.20c double plain flap. Rearward gap, sealed; δ_2 , 0°.

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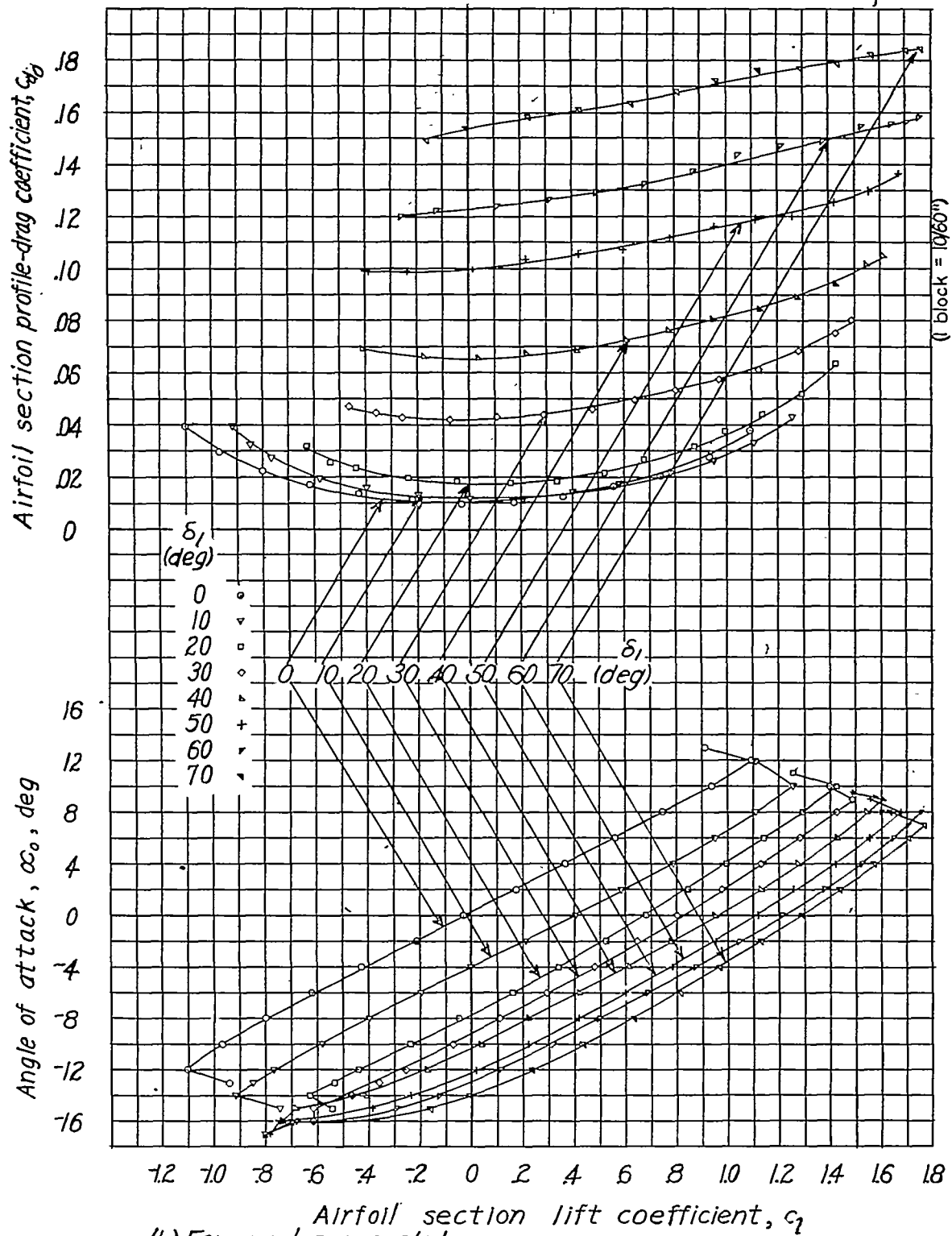
Fig. 6a
(concl'd)

(a) Concluded. Forward gap, 0.005c.

Figure 6.-Continued.

NACA

Fig. 6b



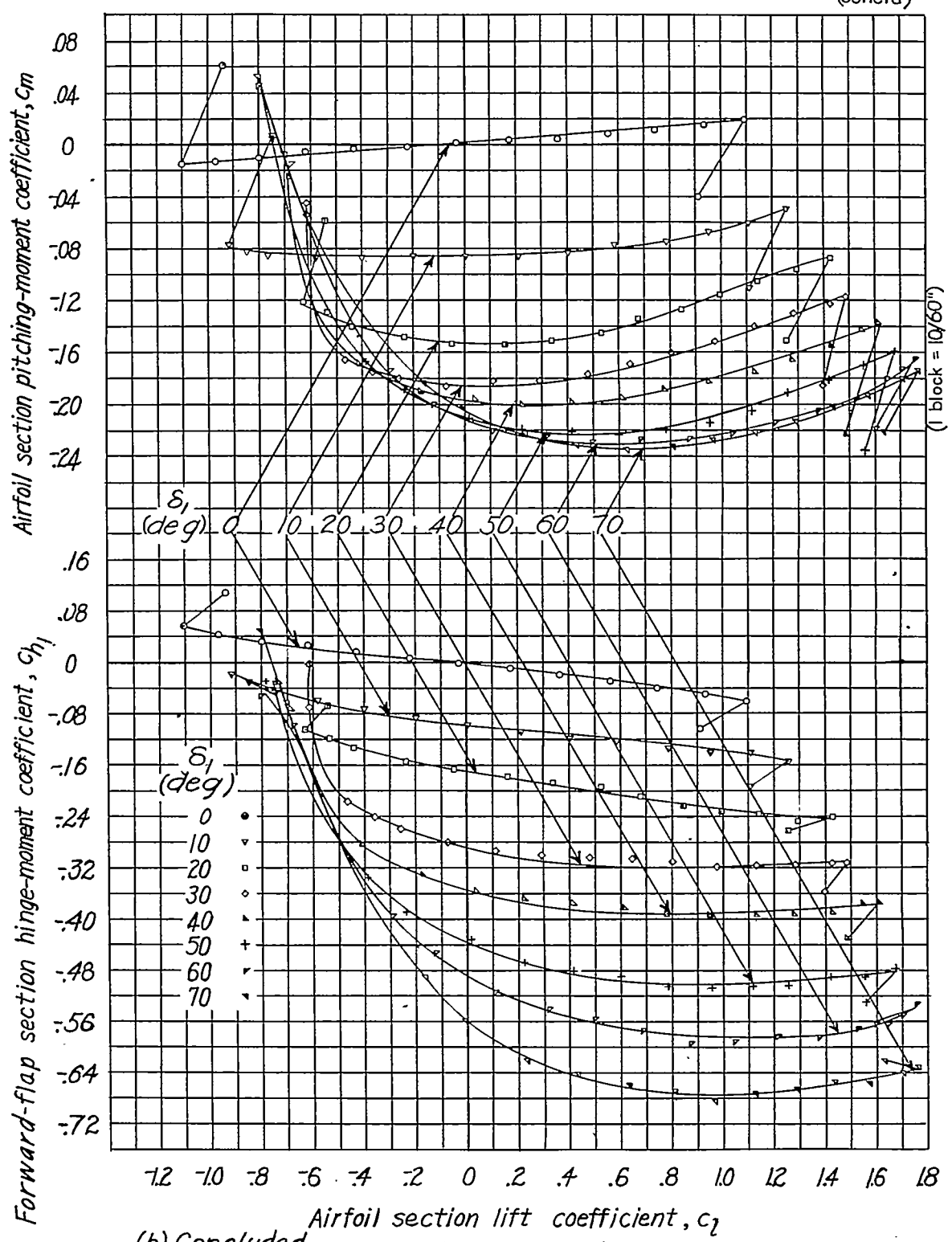
(b) Forward gap, sealed.

Figure 6.-Continued.

NACA

Fig. 6b
(concl'd)

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(b) Concluded. Forward gap, sealed.

Figure 6.- Concluded.

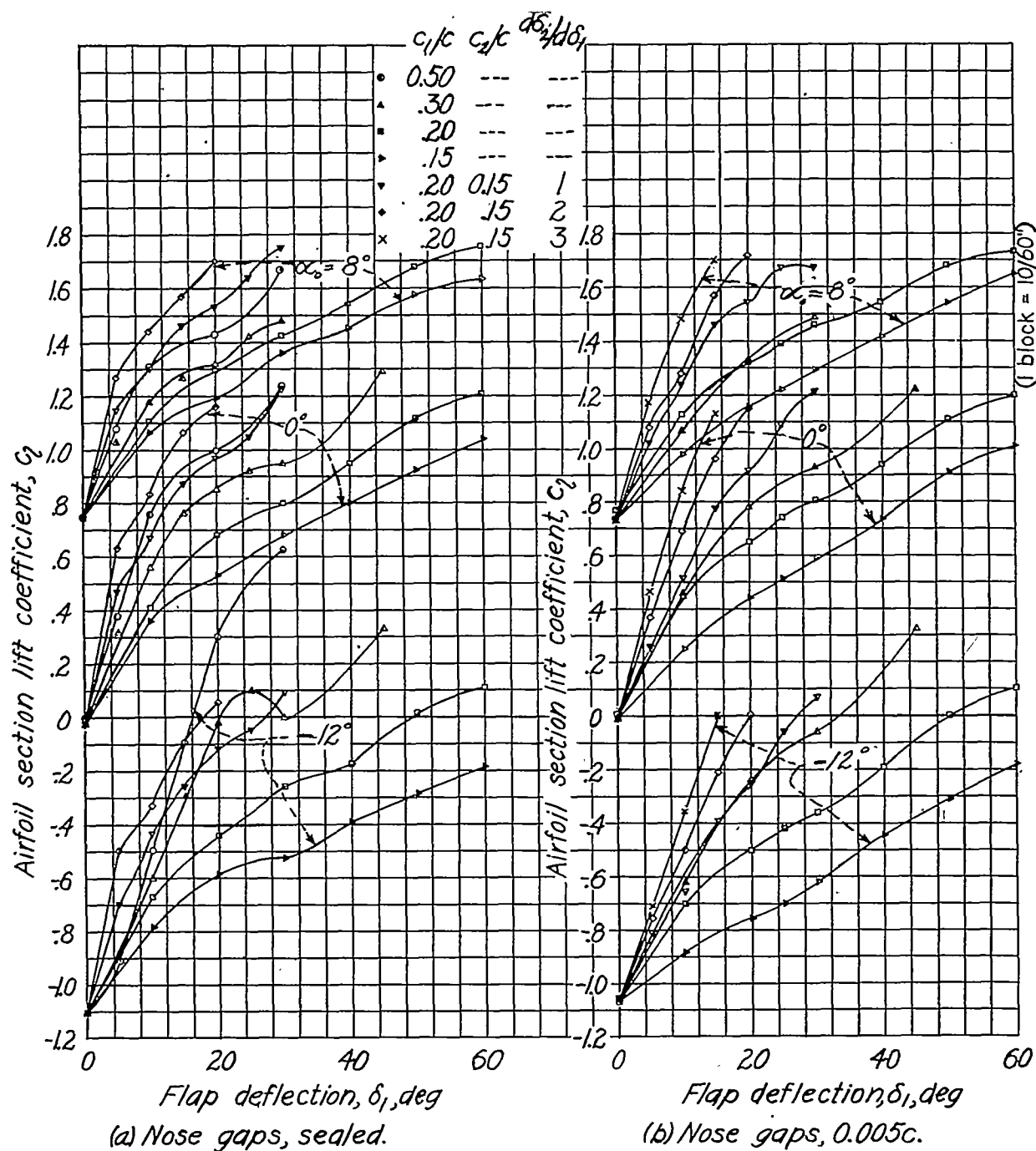


Figure 7.-Airfoil section lift coefficient as a function of flap deflection for various flap arrangements on an NACA 0009 airfoil.

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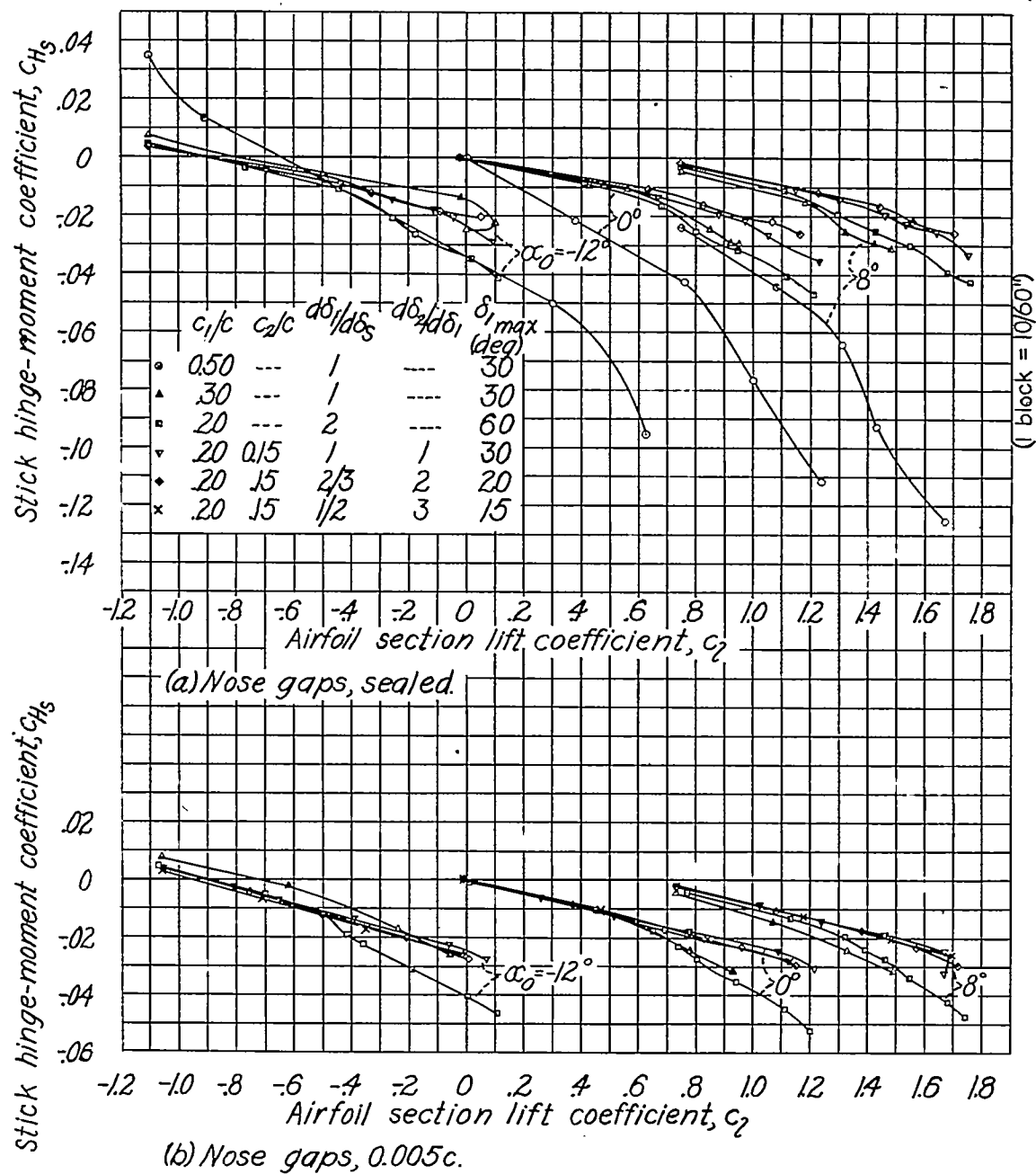


Figure 8.- Stick hinge-moment coefficient as a function of lift coefficient for various flap arrangements on an NACA 0009 airfoil.

$\delta_{s,max} = 30^\circ$

$$c_{H_S} = \left[c_{H_1} \left(\frac{c_l}{c} \right)^2 + c_{H_2} \left(\frac{c_l}{c} \right)^2 \frac{d\delta_2}{d\delta_1} \right] \frac{d\delta_1}{d\delta_s}$$

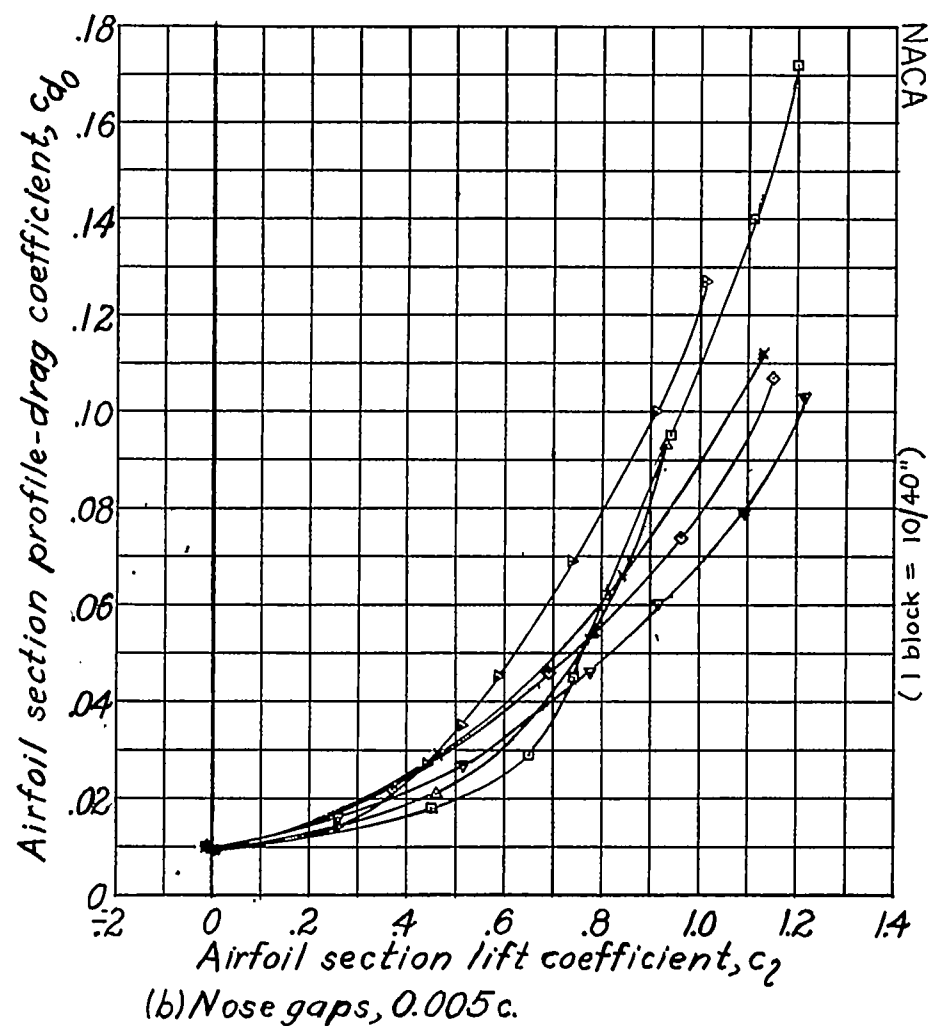
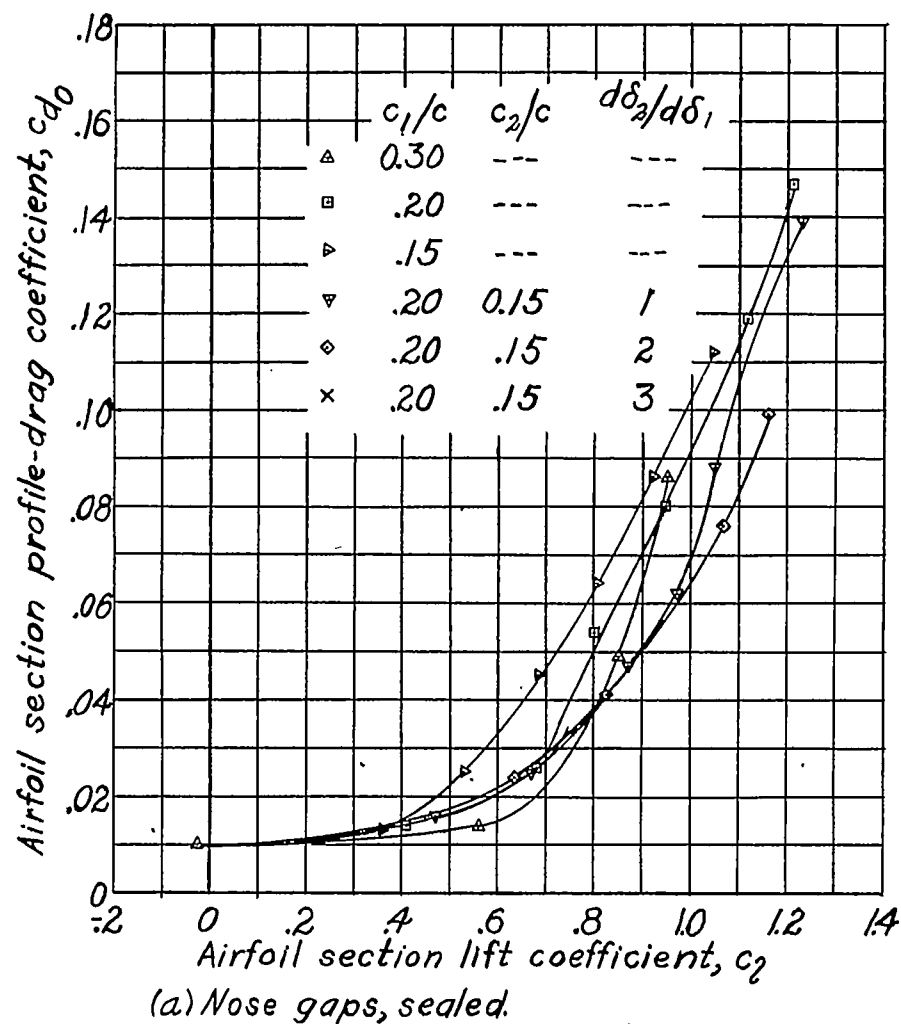


Figure 9.-Airfoil section profile-drag coefficient as a function of lift coefficient for various flap arrangements on an NACA 0009 airfoil. $\alpha_0 = 0^\circ$.